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On the Currents South off Hokkaidō in the Western North Pacific

By

Jirō SUGIURA

Hakodate Marine Observatory

1. Introduction

In the sea to the eastward off northern Japan currents of three kinds are flowing to the north of the Kuroshio main current. They are, (a) the northern branch of the Kuroshio Extension which branches off from the Kuroshio main current and flows north, (b) the Oyashio cold current which flows from the northeast to the south, and (c) the Tsugaru warm current which flows from the northwest and follows the eastern coast of northern Japan to the south.

The transported volumes of these three currents are small compared with that of the Kuroshio main current and each amounts to about one fourth of it. As the transport volumes of these three currents are nearly equal with each other, both the boundary between the northern branch of the Kuroshio Extension and the Oyashio current (the so-called Oyashio front) and the boundary between the Oyashio current and the Tsugaru warm current are rather movable and unstable ; thus the sea area between the Kuroshio main current and southern coast of Hokkaidō where these three currents mix with each other shows remarkable variations. These variations of sea conditions exert great influence on the fisheries as well as the climate of northern Japan.

In order to investigate these remarkable variations more minutely, since November 1949 the research ship Yūshio-maru (143 tons) of the Hakodate Marine Observatory occupied this sea area as far eastward as Long. 147°E four times every year at regular intervals ; since March 1954 the research ship Ryōfū-maru (1200tons) of the Japan Meteorological Agency has participated in similar routine observations of the sea area as far as Long. 150°E. These two ships' observations are improved in the following points in comparison with previous observations of the same sea area upon which the extensive works of Uda (1935, 1938) and Saito (1952) were based.

- (1) Periods of observations are not limited only in summer but they cover every season of each year.
- (2) Data of eight years have been accumulated from the beginning of the Yūshio-maru's observations till October 1957.
- (3) Intervals between stations are always less than 50 miles and sometimes are as small as 25 miles.
- (4) Most stations are observed to the depth of 1000m through all seasons except in coastal waters.
- (5) Depths of observed layers below 200m are always ascertained by the unprotected reversing thermometers; chlorinity is determined carefully by the standard method.
- (6) Since 1955, modern instruments such as a bathythermograph (BT) and a geomagnetic electrokinetograph (GEK) are used.

In addition to the data of the two ships, other data which are superior in above mentioned points (3)~(6) obtained by ships of the Maritime Safety Agency and other organizations are used in the study of the oceanic conditions of this sea area.

Based upon data obtained by these recent improved observations the detailed structure of the three currents is described in the light of recent researches of the Kuroshio System based upon the data gathered by the Ryōfū-maru and other ships.

2. *Volume transport of the currents*

Relative volume transports of the three currents above mentioned have been calculated in many periods between 1946 and 1954 as a factor indicating the intensity of the currents (Sugiura 1954, 1955a, 1955b, 1957a). The term "intensity of the currents" or "strength of the currents" has often been used by Uda (1938) and others in their discussion about fluctuation of sea conditions south off Hokkaidō. The meaning of the term is rather ambiguous, but it seems to mean magnitude of effect of the currents bringing about change in sea conditions. In the polar frontal zone, fluctuation of sea conditions mainly results from advection, and generally the effect of the advection is closely related to transport volume of the currents. For this reason "intensity of the currents" may be expressed more accurately by the transport than by other factors such as temperature or extension area. In fact, computation of the transport is im-

portant for research on fluctuation of the sea conditions as well as for forecasts of fluctuation. For example, it is ascertained that, the larger the transport of the Kuroshio main current east off Shiroyazaki (on the parallel of Lat. 37°N) is in early spring, the warmer the sea south off Hokkaidō becomes in midsummer (Sugiura 1957 d). On the other hand calculation of transport is advantageous because the volume transport between two stations depends only on the geopotential anomalies at the two stations and it is independent of the distribution of mass in the interval between the stations. But as Moriyasu (1958) has pointed out, there are certain problems which must be taken into consideration. First of all, the absolute transport can be computed only if the velocity of deep layer current is measured directly, but no such data are yet available in this sea area, only the relative values of transport are known there. However that may be, Sverdrup (1942) prepared a transport chart of the North Pacific. He stated that the transport numbers above 1500 meters include the motion of the Upper and the Intermediate Water because the Intermediate Water of the Pacific appears to flow in general in the same direction as the Upper Water. The author presented a modified transport chart above 1500 meters in the manner of the Sverdrup's chart (Sugiura 1958b). On the other hand, approximately linear relations among the transports referred to the layers of different decibars were found in the sea adjacent to Japan (Masuzawa 1957, Sugiura 1957c, Moriyasu 1958). Assuming such a linear relation, even the transport above 800 meters may be used instead of transport above 1500 meters including the motion of the Upper and Intermediate Water. But precisely speaking, the ratio of transport above 800 meters (T_8) to that above 1500 meters (T_{15}) changes in various current regions as will be seen from Table 1. Namely, according the data of the Komahashi in 1933 and 1934, the Yūshio-maru in 1951 and 1953 and the Shinnanmaru in 1951, the ratios T_8/T_{15} at 7 stations in the Oyashio current were limited between 0.37 and 0.53 and the ratios at 6 stations in the Kuroshio main current between 0.60 and 0.85. So, if the transport above 1500 meters may coincide with the absolute transport of the Upper and Intermediate Water, then in the chart of transport above 800 meters, the transport value of the Oyashio current will be estimated too small and the value of the Kuroshio main current will be too large. In fact, from Table 1 the mean value of T_{15} of the Oyashio current, 12.5 million m^3/sec , is about half of the mean value of T_{15} of the Kuroshio main current, 24.7 million m^3/sec , but the mean value of T_8 of the

Table 1.

Current region	Year	Ship	Stations	Lat. (N)	Long. (E)	Interval of the stations (naut. miles)	Direction of current	Volume transport (million m ³ /sec)		T ₈ /T ₁₅	T ₁₅ /T ₈
								above 800m (T ₈)	above 1500m (T ₁₅)		
Oyashio current	1933	Komahashi	M	43°-23'	147°-03'	116	S	5.5	10.7	0.51	1.96
			165	43°-23'	149°-42'						
	"	"	Ho	44°-16'	150°-09'	56	WNW	7.5	15.9	0.47	2.11
			165	43°-23'	149°-42'						
	"	"	Ho	44°-16'	150°-09'	104	SSW	5.7	15.3	0.37	2.70
			Ri	43°-38'	152°-23'						
	1934	"	91	40°-30'	143°-17'	60	W	2.9	7.1	0.40	2.49
			73	39°-32'	142°-56'						
	1951	Yushio-maru	344	41°-00'	144°-00'	49	SE	6.2	15.0	0.41	2.44
			336	41°-30'	144°-51'						
Kuroshio main current	"	"	344	41°-00'	144°-00'	83	SSE	5.5	13.8	0.40	2.50
			337	41°-31'	145°-41'						
	1953	"	687	41°-30'	143°-52'	63	SSE	5.0	9.5	0.53	1.89
			685	41°-56'	145°-08'						
								Mean 5.5	12.5	0.44	2.26
	1933	Komahashi	58	37°-00'	143°-31'	169	SE	19.0	24.3	0.78	1.28
			83	38°-18'	146°-38'						
	1934	"	20	35°-12'	142°-26'	50	NNE	16.3	19.1	0.85	1.17
			16	35°-32'	141°-30'						
	"	"	36	35°-38'	144°-18'	89	ENE	22.0	30.4	0.75	1.33
Kuroshio main current	"	"	49	37°-00'	143°-36'						
			36	35°-38'	144°-18'	48	NNE	21.5	29.4	0.73	1.36
	"	"	33	35°-48'	143°-20'						
			23	34°-50'	143°-49'	62	ENE	22.6	33.4	0.68	1.48
	"	"	33	35°-48'	143°-20'						
	1951	Shinnan-maru	2	38°-19'	144°-07'	50	S	7.0	11.7	0.60	1.67
			3	38°-16'	145°-11'						
								Mean 18.1	24.7	0.73	1.36

Oyashio current, 5.5 million m³/sec, is about one-third of the mean value of T₈ of the Kuroshio main current, 18.1 million m³/sec.

A second kind of error in computing transport is as follows; when a so-called multiple current is formed, the locality of the station may have influence on the estimated value of transport. That is, in order to isolate the transport of the main current from that of the counter current, a station must be located just at the boundary of the two currents. Finally, the transport of a current often varies along its course of flow. In such case, different sections across the current may give different values of transport.

In spite of the three kinds of errors above mentioned, computed relative transport can indicate the intensity of the current suitably when the computations are carefully made.

3. *The northern branch of the Kuroshio Extension*

Uda (1935, 1938) reported "the branch of Kuroshio B" which diverges from "the Kuroshio main current A" and flows to the north along the meridian of Long. 144°E . Sverdrup (1942) named it the "Northern branch of the Kuroshio Extension".

It is shown by a chlorinity chart averaged from eleven years data gained between 1946 and 1956 that the region of the northern branch of the Kuroshio Extension is reduced in March and widened in August as well as in November. That is, to the west of Long. 147°E , the northern limit at which the maximum chlorinity observed in the upper 150m layer reaches the value 18.80‰ , is located at 40°N in March, at 40.5°N in May, and at 41.5°N in August and November on the average (Sugiura 1957b).

Although this branch often appears as a continuous branch connected with the Kuroshio main current in the temperature chart based upon unsuitable observational networks, it appears always as an isolated anticyclonic eddy in the dynamic topographic chart or in the Q-chart (Sugiura 1954, 1955a, 1955b). Kawai (1955) called it "the warm water mass in the transition area" and Masuzawa (1957) called it "the warm eddy north of the Kuroshio".

Especially the large warm eddy which appeared to the east off Cape Kinokan in 1954 has been noticed and analysed in detail by Masuzawa (1955a, 1955b, 1957), Ichiye (1956a) and others. Warm eddies which were observed from summer to autumn 1943 are discussed by Ichiye (1956c). It is shown that transport of the warm eddy to the north of Lat. 39°N is small in spring but becomes large in summer and autumn on the average (Sugiura 1957a). That is to say, from computed transport of the warm eddies near the locality of Lat. 40°N , Long. 144.5°E referred to 800m layer in 17 periods between 1946 and 1954, it is shown that the maximum value from 5 periods in spring is 4 million m^3/sec , that from 4 periods in summer it is 11 million m^3/sec , and that from 8 periods in autumn it is 15 million m^3/sec .

A warm eddy which appeared in spring and summer of 1950 is worthy of note because its locality shifted to the north and because of its fairly large transport. Shoji (1951) reported that an isolated anticyclonic eddy of the Kuroshio water of a depth of 400~500m was located southeast off Erimo-misaki in August of that year. Kawai (1955) explained that this eddy was formed in March to April by a meandering part of the Kuroshio front and was cut off

from the Kuroshio main current by the second branch of the Oyashio. An explanation from a different angle has been given on the basis of the data of five observations taken during 6 months from March to August 1950 (Sugiura 1954, 1957b). Evidence is given that a small eddy which had been formed before April, being supplied warm water from the south in May, grew into a large eddy in June. Ichiye (1956b) argued that large vertical stability promotes surface drift. Conversely it is presumed that a warm water mass moved by southerly wind is apt to accumulate on a warm eddy which previously existed owing to small vertical stability. The supply of warm water in May above mentioned may be caused by a remarkable meandering of the Kuroshio main current. Indeed, in May the Kuroshio main current appeared as a large anticyclonic vortex with its center in the locality of Lat. 37°N , Long. 143.5°E ; its transport amounted to 30 million m^3/sec above 800m.

There is another matter to be noted. Takenouti (1957) emphasized that in the summer of 1950 a very thin surface layer of warm water extended to the north in the eastern sea off northern Japan. It has been shown that such thin warm surface water was distributed only to the south of the warm eddy off Erimo-misaki above mentioned, and that the thin layer was the Oyashio water heated by solar radiation (Sugiura 1957b).

4. *The Oyashio cold current.*

Although the water mass of the Oyashio current has been analysed by many oceanographers such as Suda (1934), Uda (1935, 1938), Saito (1952), Masuzawa (1952) and Hirano (1957), comparatively little has been known about the details of branches and the transport of the Oyashio current. It is shown by a dynamic topographic chart based upon the data of the Komahashi in 1934~1936 that the Oyashio current flowing along the Kurile Islands in the sea to the east off northern Japan consists in part of a large cyclonic circulation in company with the Aleutian current flowing east and the westward moving current along the Aleutian Islands (Sugiura 1958b). The volume transport of the Oyashio current off the southern Kurile Islands amounts to 15 million m^3/sec above 1500m based upon the stations occupied by the Komahashi in June 1935 (Sugiura 1958b). The transport of the Oyashio current to the south of Erimo-misaki amounts to 13 million m^3/sec above 1200m based upon data from the stations occupied by the Yūshio-maru in May 1951 (Sugiura 1957c).

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It has been shown by GEK observations since 1955 that the maximum velocity of the Oyashio current south off Hokkaidō to the west of Long. 147°E is 1.3 knot and that the width of the strongest current is restricted to only 10-15 miles (Sugiura 1957c).

The Oyashio counter current flowing northeast along the south side of the Oyashio main current flowing southwest can be distinguished (Sugiura 1956, 1957c). These two branches of the Oyashio current are not differentiated by temperature chart but are clearly distinguishable by the dynamic topographic chart. Southward transport of the cold Oyashio water is given by difference of the transport of these two branches of the Oyashio current. So it is unreasonable to neglect the Oyashio counter current.

Cyclonic eddies are often observed on the boundary between the two branches of the Oyashio current occurring with an upwelling of deep water. For example, iso- σ_t surface of 27.2 rose by about 400m in a distance of 40 miles within an eddy south off Kushiro in February 1955 (Sugiura 1957 c).

The Oyashio littoral current can be distinguished from the Oyashio main current (Sugiura 1956, 1957c). In spring the coastal water of the littoral current which was firstly noticed by reason of plankton distributions is less haline than the Oyashio water of the main current and is warmer than it in autumn. It is presumed that the Oyashio main current originates from north of the middle Kurile Islands while the Oyashio littoral current arises from near the southern Kurile Islands because both intermediate temperature and subsurface chlorinity in the main current attain a minimum in summer, while both in the littoral current show a minimum in spring (Sugiura 1956, 1957c).

Recently Kawai (1955), Masuzawa (1956a, 1956b, 1957, 1958) and Ichiye (1956c, 1956d) have reported the existence of the so-called inner cold water along the northern edge of the Kuroshio main current in the eastern sea off northern Japan. It is presumed that the Oyashio coastal branch and the Oyashio off shore branch often correspond to the inner cold water along the eastern edge of the Tsugaru warm current and the southward flow of "the warm eddy north of the Kuroshio" respectively. For instance, in March 1957 east off Miyako, along the eastern edge of the Tsugaru warm current which was flowing to the southeast at a velocity of 1.0 knot, a very cold and low chlorinity body of Oyashio water was flowing to the same direction at a velocity of 0.7 knot. Similar velocity profiles were found by the dynamic calculations made in November 1949 and August

1953 (Sugiura 1958a).

5. *Tsugaru warm current.*

Tsugaru warm current flows out eastward through the Tsugaru Straits. The minimum section of the straits has a width of 10 miles and a depth of 120m. As Uda (1938) has pointed out already, the effect of the Tsugaru warm current on the oceanic conditions of the sea to the east of Japan is comparable to the effects of the Oyashio as well as of the Kuroshio.

Many similarities between this current and the Kuroshio main current are shown using recent data of BT and GEK (Sugiura 1958a). For instance, as above mentioned, this current often flows along the Oyashio coastal branch corresponding to the inner cold water along the Kuroshio main current. A warm core having a thickness of more than 200m and a width of about 15 miles was found along the Tsugaru warm current in October 1956.

Moreover, it is observed by cooperation of the Ryōfū-maru and the Yūshio-maru in February to March 1957 in the sea adjacent to Iwate Prefecture that a front between the Tsugaru warm current and the Oyashio current shifted southward very rapidly for a distance of 40 miles within seven days (Sugiura 1958a).

6. *Concluding remarks.*

Uda (1938) described the general features of hydrographical conditions in the North Pacific northeasterly adjacent to Japan, and discussed the Kuroshio main current and its branches, the Oyashio current, the Tsugaru warm current and two boundary zones among them. But as his study was based mainly on data of water temperature in upper layer and comparatively limited data of chlorinity as well as current velocity, his interpretations are not always perfect. For instance, he stated that the region of the northern branch of the Kuroshio Extension is widened in summer and reduced in autumn and winter; but consideration of a chlorinity chart shows that in autumn the region of the branch is as wide as in summer (Sugiura 1957b). To take another example, he maintained that the northern one of two strong eastward moving current zones on a meridian of Long. 144.4°E south off Kushiro corresponds to a boundary between the Oyashio current C and the Tsugaru warm current D which is affected by the northern branch of the Kuroshio Extension B; but it is doubtful whether the Tsugaru warm current extends eastward to the meridian of Long. 144.4°E south

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off Kushiro. The eastern limit of the Tsugaru warm current is seen on the average at Long. 142.8°E in summer and at Long. 143.3°E in autumn (Sugiura 1957b).

Saito (1952) investigated the Oyashio current in the light of the fact that the currents near the polar front form a part of the general circulation of the North Pacific. He stated that the intermediate waters in the Okhotsk and the Bering sea have come to mix with one another through lateral mixing in the Oyashio current region. About the velocity distribution in the northwestern sea region, he said roughly that the current in winter is less than in summer. But as mentioned above, seasonal fluctuation of various current branches is much more complicated. For example, the transport of the northern branch of the Kuroshio Extension and the Tsugaru warm current reaches maximum in autumn while the transport of the Oyashio current reaches maximum in winter (Sugiura 1957a).

Hirano (1957, 1958) showed over-all patterns of horizontal distributions of oceanographic properties including temperature, salinity and dynamic depth in spring and summer on the basis of the data obtained in the northwestern Pacific during 1929 to 1954. He suspected that the waters in the western subarctic sea region may have their origin in the Gulf of Alaska. Hirano gave a transport chart above 800 meters in the western North Pacific. The chart generally coincides with a transport chart above 1500 meters by the present author (Sugiura 1958b). But the currents in the sea south off Hokkaidō Hirano discussed rather roughly.

Kitano (1958) showed a schematic oceanic model of northern North Pacific Ocean based upon the data obtained in 1934~1936 and 1956~1957. His results generally coincide with those which had been given by Hirano and others.

As above mentioned, the general circulation of the northern North Pacific has recently been studied by Saito, Hirano, Kitano and others, and the warm eddy north of the Kuroshio by Masuzawa (1955a, 1955b, 1957), Ichiye (1956a) and others. But comparatively little work has been done on the Oyashio current and the Tsugaru warm current at any time since Uda (1938) studied these currents. In the present paper the detailed structure of the three currents in the sea south off Hokkaidō has been reported upon the basis of recent improved observations. The results are indispensable for the research on the fluctuations of sea conditions south off Hokkaidō as well as for the forecast of the fluctuations.

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Supplementary Note on the Dynamical Property of the Cold Water Region

By

Shigeo MORIYASU

Kōbe Marine Observatory

1. *Introduction*

For the discussion on the fluctuation of the cold water region in Enshū-nada, it is significant to compute the indicator for its intensity. Since there is a counter-clockwise eddy in the region (MORIYASU, 1958), it is appropriate to use the dynamical property of the eddy. MCEWEN (1948) computed the radius, the angular momentum and the kinetic energy of the eddy off southern California, and ICHIYE (1954) obtained them of the cold water region south of Honshū. We proposed a simplified method based on some assumptions in the previous paper (MORIYASU, 1957), but the discussion on the method was not made. We intend to consider whether our method is useful or not. Therefore, this paper is taken to be a supplementary note on the previous paper. Furthermore, we will describe briefly the fluctuation of the eddy in 1954-1956, and compare our results with theirs.

2. *The fluctuation of the cold water region in 1954-1956*

The cold water region appeared frequently in the concerned sea area as pointed out by many oceanographers. The duration of the region is not constant. The temporary region vanishes within several months (ICHIYE, 1955), while the durable one continues about ten years (UDA, 1949). The region treated here is stable and its duration is fairly long.

It can not be made clear when the cold water region discussed here occurred, because the observations were not carried out frequently for years after the close of World War II. Though it was at the beginning of June, 1954 that the existence of the region was ascertained (K.M.O., 1955), the region seemed to occur prior to this time. The stream axis of the Kuroshio off Shiono-misaki moved abruptly off-shore in June, 1953 (MASUZAWA, 1954). This phenomenon is

considered to be in connection with the occurrence of the region. Since June, 1954, the observations have been frequently carried out over the sea south of Honshū and so the conditions have been made clear.

We will briefly describe the fluctuation of the cold water region by using the results of the observations, which have been carried out by Japan Meteorological Agency, Kobe Marine Observatory and Hydrographic Office. Fig. 1 shows the position and the area of the cold water region which are determined on the geopotential topographical chart of the sea surface referred to the 800 db surface.

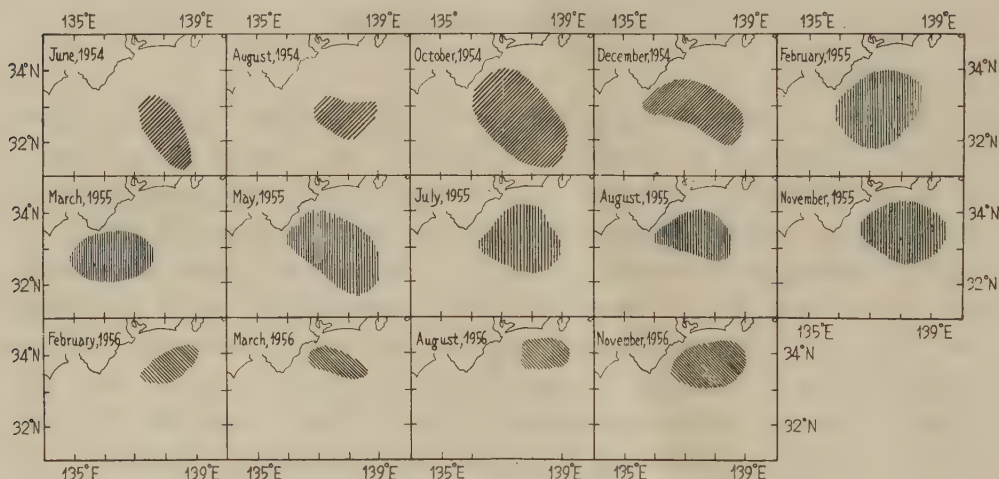


Fig. 1. The fluctuation in the position and the area of the cold water region.

The shaded portion is the cold water region on the geopotential topographical chart of the surface referred to the 800 db surface.

1954—The region extended off-shore in general. The area fluctuated remarkably and its maximum was found in October.

1955—The region was generally situated north of 32°N and the westward extension was seen at the beginning of the year. The area was nearly the same as in 1954. The long axis of the region was in east-west direction in the second half of the year.

1956—The region was situated north of 33°N. The area was diminished except for in November. In August, the existence of the region was somewhat vague. Thereafter, the region was generally decayed and its existence was occasionally indistinct. And we do not treat the fluctuation in the period. The features stated above indicate that the fluctuation is striking when the region is large and that the region is predominant in autumn.

3. *The discussion on the method of computation*

The method of computation was stated in the previous paper (MORIYASU, 1957). And so, using the same notations, we show only the results as follows:

$$D = D_0 + ar^2,$$

$$\delta D = D_R - D_0 = aR^2,$$

$$\zeta = -f + \sqrt{f^2 + 8a},$$

$$A.M. = M = 2\pi \int_0^R r^2 q dr = \frac{\pi}{4} \zeta R^4,$$

$$K.E. = K = 2\pi \int_0^R r \left(\frac{q}{2} \right)^2 dr = \frac{\pi}{16} \zeta^2 R^4.$$

Here,

$$a = \frac{1}{4} \left(f\zeta + \frac{1}{2} \zeta^2 \right).$$

The vorticity, the angular momentum and the kinetic energy are represented in C.G.S. units.

Table 1 shows that the values of angular momentum and of kinetic energy by our method agree considerably with the values by McEWEN's method. The value of angular momentum by our method is from 90% to 110% of that by McEWEN's method and the satisfactory result is obtained. The value of kinetic energy by our method is smaller than 80% of the value by McEWEN's method in some cases and the difference between them is generally larger as compared with the difference in angular momentum. The standard deviation of the ratio of kinetic energy by our method to by McEWEN's method is about twice the standard deviation of the ratio of angular momentum. Therefore, we can not obtain a satisfactory result as to the kinetic energy. But, our method may be used for the rough estimation and the results by two methods show the tendency similar to each other. And then, the values by our method are sufficient indicators for discussing the fluctuation of the eddy in the cold water region. As stated above, however, our method is based on simple assumptions and so the treatment may be unsuitable for discussing the structure of the eddy in detail.

Next, we will estimate the error of those elements. As the elements are computed from R and a , we must determine their errors. In the example in October, 1954, the computed constants and their errors are as follows:

$$\Delta D_0 = 1.21 \pm 0.0094 \text{ dyn. m},$$

$$a = (2.17 \pm 0.062) \times 10^{-5} \text{ dyn. m/km}^2.$$

The error of R is assumed to be 5 km. Then,

$$\frac{\Delta a}{a} = 2.9 \times 10^{-2},$$

$$\frac{\Delta R}{R} = 4 \times 10^{-2}$$

are given. Accordingly, the errors of various elements are estimated as follows:

$$\frac{\Delta(\delta D)}{\delta D} = \frac{\Delta a}{a} + 2 \frac{\Delta R}{R} = 1.1 \times 10^{-1},$$

$$\frac{\Delta \zeta}{\zeta} = \frac{\Delta a}{a} = 2.9 \times 10^{-2},$$

$$\frac{\Delta M}{M} = \frac{\Delta \zeta}{\zeta} + 4 \frac{\Delta R}{R} = 1.9 \times 10^{-1},$$

$$\frac{\Delta K}{K} = 2 \frac{\Delta \zeta}{\zeta} + 4 \frac{\Delta R}{R} = 2.2 \times 10^{-1}.$$

The result shows that the errors of angular momentum and of kinetic energy are more than others.

4. The consideration concerning the results

The values of the elements in Table 1 are based on the data of 14 observations in 1954-1956. We can not find remarkable characteristics in the table. However, there may be tendencies as follows:

- (1) the region is predominant in autumn, while it is not in summer;
- (2) the vorticity is great when the radius is small.

The first feature is not the physical expression, but it is no more than the representation about the seasonal fluctuation of the elements. The relation between the vorticity and the radius is shown in Fig. 2. The scatter is considerably seen, but the correlation coefficient is -0.529 . Since the significance point of 5% is 0.5139 for $N=14$, the correlation can be admitted at the level.

Furthermore, the table verifies the features of fluctuation stated in section 2. Namely, the inspection of the geopotential topographical chart gives us the same features as those shown by the computed properties. And, the cold water region seems to be most predominant in autumn of 1954.

According to the research on the eddy off California by McEWEN (loc. cit.), the radius is less than 100 km, and the order of angular momentum and of kinetic energy are 10^{21} and 10^{15} , respectively. Though the results are referred to the 500 db surface, it may be concluded that this eddy is of smaller scale than the

S. Moriyasu: Supplementary Note on the Dynamical Property of the Cold Water Region

Table 1. Computed values of the elements of the eddy in the cold water region.

(*a*: by MCEWEN's method; *b*: by our method)

	$R \times 10^{-5}$	$\zeta \times 10^6$	$\delta(\Delta D)$	$A.M. \times 10^{-28}$			$K.E. \times 10^{-17}$		
				<i>a</i>	<i>b</i>	<i>b/a</i>	<i>a</i>	<i>b</i>	<i>b/a</i>
			dyn. m.						
1954, June	81	1.17	0.16	0.43	0.40	0.93	1.39	1.16	0.84
Aug.	73	1.42	0.17	0.34	0.32	0.94	1.35	1.13	0.84
Oct.	138	1.02	0.39	2.69	2.91	1.08	6.73	7.41	1.10
Dec.	123	0.71	0.23	1.35	1.28	0.95	3.18	2.25	0.72
1955, Feb.	121	0.84	0.25	1.34	1.37	1.02	2.63	2.89	1.10
Mar.	101	1.12	0.24	0.88	0.92	1.05	2.46	2.55	1.04
May	126	0.67	0.22	1.42	1.33	0.94	2.27	2.23	0.98
July	107	0.83	0.19	0.82	0.85	1.04	2.33	1.78	0.77
Aug.	90	0.82	0.14	0.43	0.42	0.98	0.92	0.86	0.94
Nov.	105	1.14	0.26	1.04	1.09	1.05	2.98	3.10	1.04
1956, Feb.	70	1.25	0.13	0.26	0.24	0.92	0.73	0.74	1.01
Mar.	65	0.99	0.09	0.14	0.14	1.00	0.36	0.34	0.95
Aug.	64	1.01	0.09	0.14	0.13	0.93	0.41	0.34	0.83
Nov.	96	1.31	0.25	0.96	0.87	0.91	3.16	2.87	0.91
Mean	—	—	—	—	—	0.98	—	—	0.93
Standard deviation	—	—	—	—	—	0.055	—	—	0.116

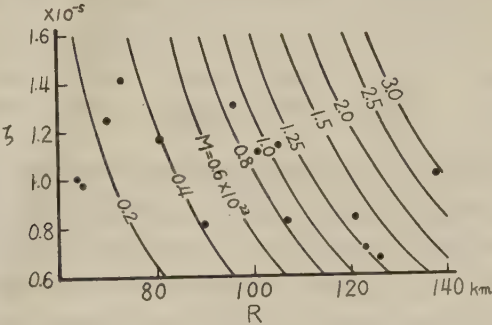


Fig. 2. The relation between the vorticity and the radius of the eddy.

The full line represents $M = \frac{\pi}{4} \zeta R^4$.

eddy off Enshū-nada. The conservation of angular momentum was found by him. If the angular momentum is conserved, the vorticity is inversely proportional to R^4 and so increases strikingly with the decrease of radius. The full line in

Fig. 2 shows the relation between the vorticity and the radius in the case that the angular momentum is conserved. Therefore, the conservation is not completely satisfied. However, it seems that the observed value of angular momentum is not found between 0.4×10^{23} and 0.8×10^{23} and that its abrupt change is found at the radius of about 90 km. Roughly speaking, if the radius is divided into two parts, the conservation of angular momentum may be admitted in each part of the radius and then the vorticity decreases with the increase of radius. The meander of the Kuroshio is striking for the radius above 90 km in general and the critical value of the radius, 90 km, may be significant from the dynamical standpoint. The value of angular momentum in October, 1954 is extraordinary. But, such a great value does not appear in other cases.

ICHIYE (1954) analyzed the eddy in this sea area in detail by using the data in nearly each month of 1940, when the cold water region was most active (UDA, loc. cit.). The radius, the angular momentum and the kinetic energy are 80~140 km, $0.2 \times 10^{23} \sim 3 \times 10^{23}$ and $0.1 \times 10^{17} \sim 5 \times 10^{17}$, respectively, where the computation is referred to the 600 db surface. The mean value and the standard deviation are shown in Table 2, which verifies that the scale of the eddy in

Table 2. The mean value of the elements of the eddy and the standard deviation in 1940 and in 1954~1956. $\bar{x}$ is the mean value and σ is the standard deviation.

	$R \times 10^{-5}$		$A.M. \times 10^{-23}$		$K.E. \times 10^{-17}$		$\zeta \times 10^5$	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
1940	125	20.1	1.121	0.801	1.674	1.453	0.55	0.212
1954~1956	97	23.4	0.875	0.683	2.117	1.736	1.02	0.219

1940 is larger than that of the eddy concerned here and that the degree of fluctuation is of nearly the same order. It must be noticed that the result in 1940 is led from the data in nearly each month while the result in 1954~1956 is based on the data in each season. However, the difference is not so significant as to affect the comparison largely. The kinetic energy is less in 1940, because it contains the square of vorticity which is less in 1940 than in 1954~1956. Here, the vorticity in 1940 is computed from the relation

$$\zeta = 4 \frac{K}{M}$$

on the assumption that the eddy is circular and has the homogeneous vorticity, and the values of angular momentum and of kinetic energy computed by ICHIYE

are used. The value of vorticity computed in this manner is about a half of value in 1954~1956. When the cold water region in 1940 is compared with the region in 1954~1956, the following differences are found:

- (1) the scale is larger in 1940;
- (2) the region in 1940 extends southwards and west of 136°E , while, in 1954~1956, it extends hardly west of 136°E , and is situated north of 32°N .

5. Summary

For the estimation of the dynamical property of the eddy, our simplified method may be used and the vorticity may be considered to be constant in the eddy. The concerned eddy is of larger scale than the eddy treated by McEWEN and of smaller scale than the eddy treated by ICHIYE. The conservation of angular momentum can not be found strictly, but there may be an abrupt change of the angular momentum at the radius of about 90 km. Since the variation of angular momentum is related to the moment of external force, we should discuss the moment of external force, and the theoretical consideration shall be made in another paper. Moreover, a few characteristic features in the fluctuation of the cold water region are drawn from the geopotential topographical chart and the computed elements of the eddy.

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A Method of Analysis for Long-wave Phenomena in the Ocean, using Hydraulic Models and Electronic and Cybernetic Techniques¹

An Electronic System for Recording and Analysing Sea Waves, Part II

By

ShIZUWO ISHIGURO

Nagasaki Marine Observatory

Abstract A method of analysis for long-wave phenomena in the ocean and the equipment for this method are described. A phenomenon to be analysed is assumed to be a 'response' resulting from an 'excitation' on the 'system', and the relations between these are analysed. A hydraulic model is used to represent the system, and electronic devices including servo-mechanisms are used to deal with the excitation and the response. By this method, it is possible to deal with long-wave phenomena including the transient states caused by arbitrary excitations on an arbitrary bottom topography.

1. Introduction

Many theoretical and experimental methods have been applied to study long-wave phenomena in the ocean, and these have, of course, their strong and weak points for each practical study. Although model methods are in general more expensive and take more time for their preparation than theoretical methods, they can more easily represent bottom topographies of the ocean, especially in case where the topography is complicated. It is not easy, however, by either theoretical or model methods to deal with the transient states of these phenomena and with cases caused by arbitrary form excitations.

The author has tried to improve model methods to make it possible to solve practical problems dealing with even these complicated cases. Thus in this

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- 1 Contribution No. 195 from the Nagasaki Marine Observatory. This work was presented at the Annual Meeting of the Meteorological Society of Japan, 9 November 1955, Tokyo.
 - 2 Part I of this series was published in *Oceanographical Mag.*, *JMA*, **9** (1957), 159-207. Part III was published in *Phil. Trans. Roy. Soc. London, A*, **215** (1959), 303-340, and the successive parts will be published in the same magazine.

paper, an experimental hydraulic model which incorporates several new techniques of electronics and cybernetics is described.

This method is being applied actually to investigate the hydraulic problems on Ariake Bay, on the west coast of Japan, where the tidal amplitudes are particularly large owing to a resonance of the natural period of the bay with an astronomical tidal period, and there is a practical need to reduce the amplitude to gain more land.

2. Basic idea and the outline of the actual equipment

The basic idea of the method is shown in Fig. 1. The original hydraulic system to be analysed is modelled in a water tank by using an ordinary dimen-

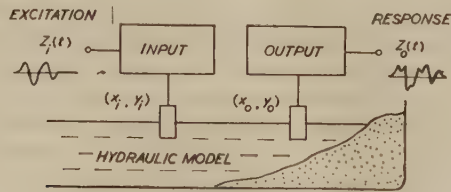


Fig. 1. Basic idea of the method.

sion-model technique. A long-wave phenomenon in this 'system' is assumed to be a 'response' resulting from an 'excitation'. The excitation which is a time function $Z_i(t)$ at a point (x_i, y_i) on the mean water level of the system, is given to the system through an input. Its response which is a time function $Z_o(t)$ at another point (x_o, y_o) is obtained through an output. If the excitation is given as any kind of waveform on any point on the system, and if its response is obtained, the relation between the system, the excitation, and the response can be applied to many practical problems, for example hydrodynamical representation of the system, derivation of the causes of the excitation, or predictions of the original phenomenon. It is possible to extend the method to more than one excitation and response point.

The actual equipment is designed to realize the basic idea as well as possible, by using some electronic, hydraulic, and optical devices. The block diagram of the equipment is shown in Fig. 2. More details of the electronic circuits of the equipment are shown in Fig. 3. The schematic diagram of the

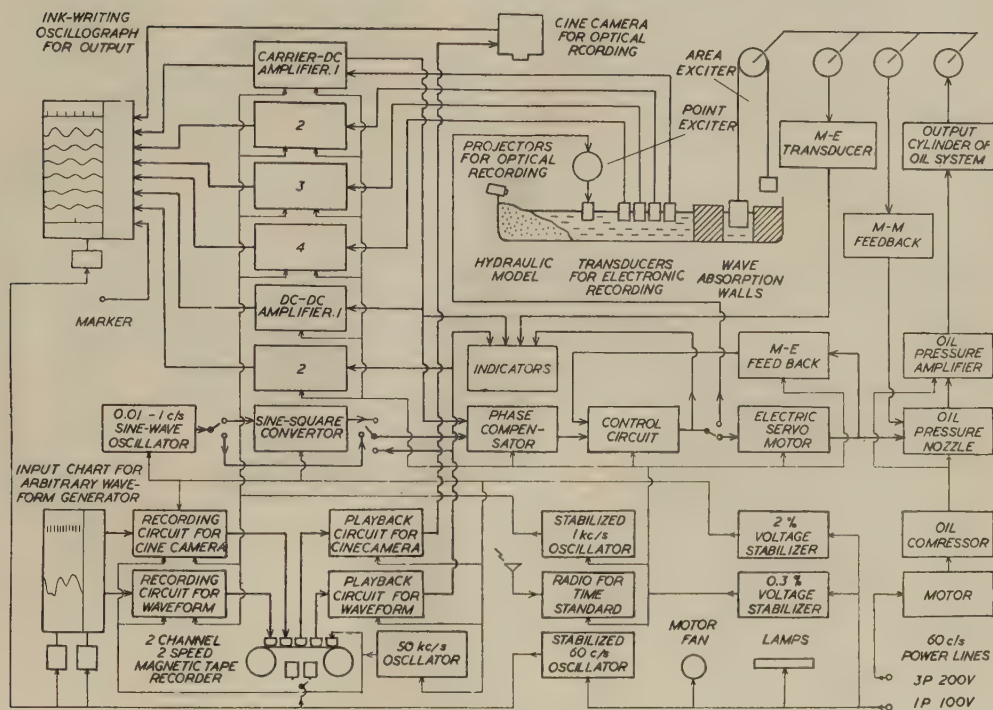


Fig. 2. Block diagram of the equipment.

equipment is shown in Fig. 4. The main parts of the electronic devices are shown in Fig. 5. The equipment can be divided into four groups: (1) hydraulic model, (2) excitation generators, (3) response recorders, and (4) associated devices.

Hydraulic model This part consists of a water tank, in which a model of the bottom topography of a particular sea area is set, and several wave-absorption walls representing a wider area of the sea in the limited space of the tank.

Excitation generators This part corresponds to the 'input' in the basic idea, and consists of some time-function-voltage generators and two kinds of water-level-control devices, a 'point exciter' and an 'area exciter', driven by the voltage generators. As the mass of the tank water is considerable, an oil-pressure system is used to drive the area exciter. To repeat tests under constant experimental conditions, function-storage devices and several stabilizers

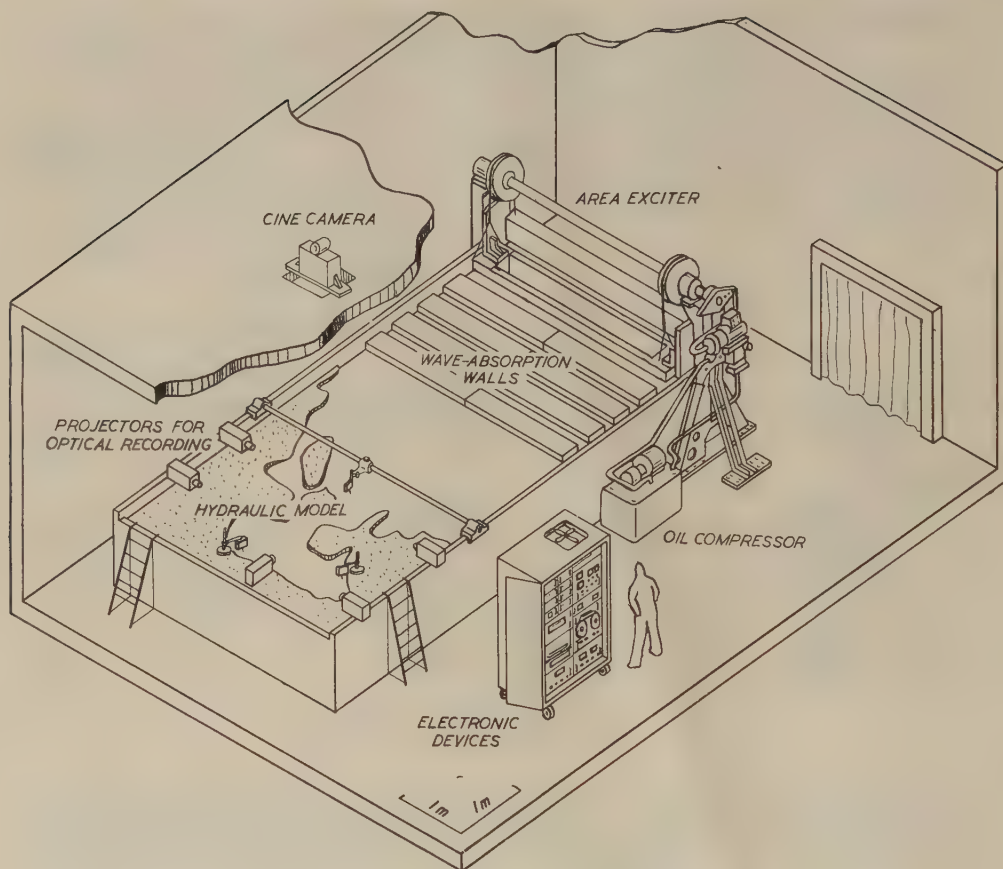


Fig. 4. Schematic diagram of the equipment.

are included in this part.

Response recorders This part corresponds to the 'output' in the basic idea, and consists of several electronic water-level recorders and an optical water-level recorder. The former is used to record the responses at several points on the model by a simple procedure. The latter is used to record two-dimensionally the response of the whole surface of the model at the same time, and requires a photographic procedure, so the equipment must be set in a room which can be made light-proof.

Associated devices In order to attain the necessary accuracy and stability, several associated devices are incorporated in the main equipment.

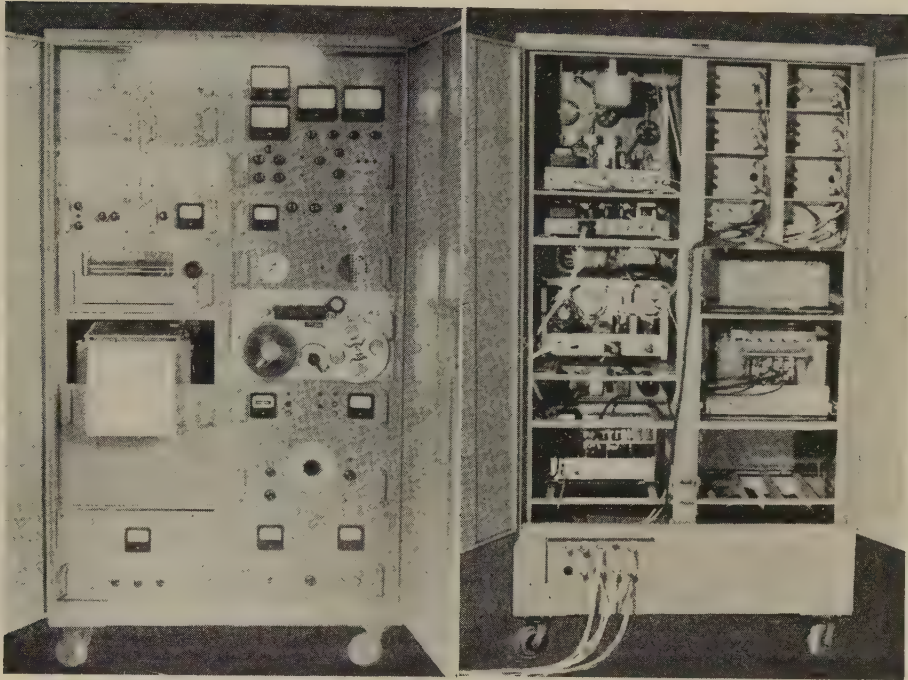


Fig. 5. Main part of the electronic devices.

3. Hydraulic model

3.1 Arrangement of models

To design a model of a bottom topography, the usual technique is used. For example, the relation between the reduction coefficients of the model, $K_v = K_h^2/K_t^2$ can be used. Where K_h , K_v , and K_t are the reduction coefficient of the horizontal scale, the vertical scale, and the time scale respectively.

An example of the arrangement of a model, taking the case of the west coast of Kyushu, is shown in Fig. 6. The dimension of the present water tank is 7.0 m in length, 3.5 m in width, and about 1 m in depth. The actual area to be modelled is about 10,000 km². The maximum amplitude of the tide in this area is about 3 m. A bay where the free oscillation of the water resonates with the period of the semidiurnal tide is included in the area. To relate the conditions on the actual hydraulic system and the model equipment, $K_v=250$, $K_t=2500$, $K_h=39528$ have been chosen. An unusually large ratio of K_h to K_v like the above leads to a low accuracy in the representation of energy losses in

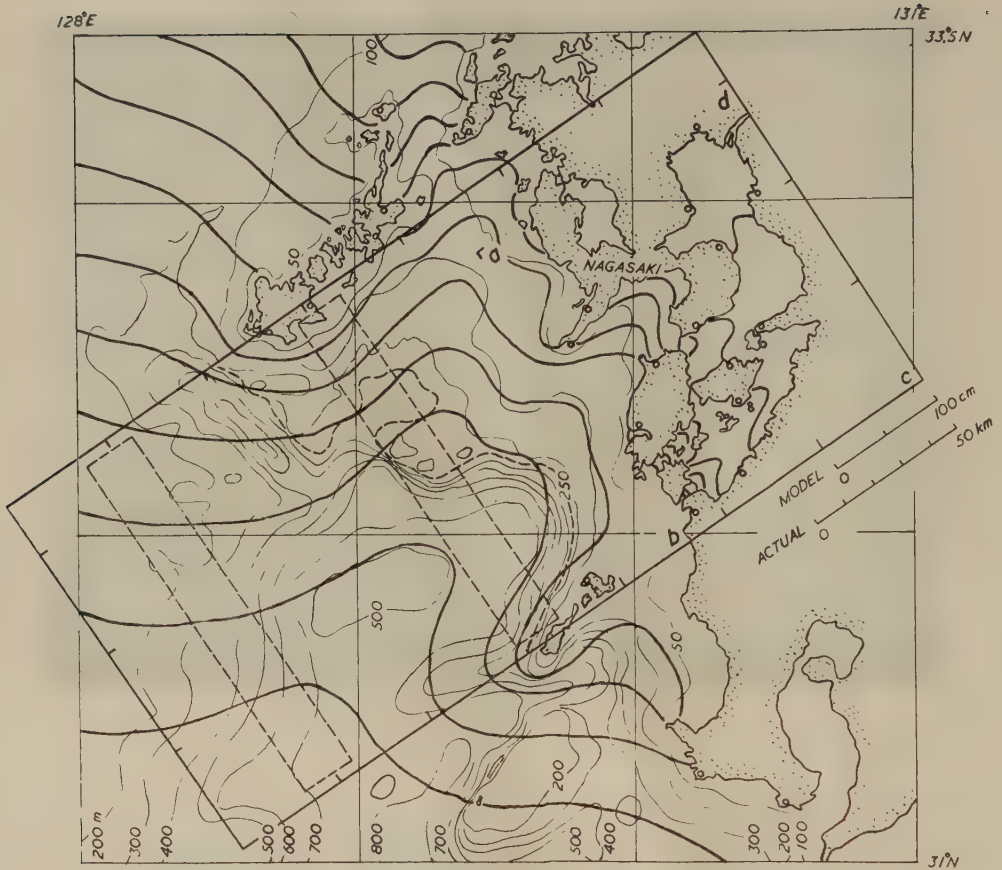


Fig. 6. Example of an arrangement of a model in the water tank.

the model. To compensate for this disadvantage, and to give the friction coefficient adequate values for various depths, thin vinylon ribbons (about $300 \times 2 \times 0.1 \text{ mm}^3$) are distributed on the bed of the model in various thicknesses and densities depending on the depth.

The most interesting area for the present investigation is shown by the rectangle a-b-c-d in Fig. 6. The co-tidal lines of M_2 near the coast are shown by the thick lines in the same figure. The area which has been modelled in the tank and two positions of an area exciter (dotted line) are also shown in Fig. 6. The model is so positioned in the tank that islands or the shallow part of the bottom topography are as near the tank walls as possible. The open sea in

the model is represented by a wave absorbing material (see 3.2) and this also keeps down the effect of free oscillations of the tank water. The bottom topography for which the depth is less than 250 m has been modelled with mortar in the tank. A part of the model is shown in Fig. 7.



Fig. 7. Example of a model in the water tank.

3.2 Wave-absorption walls

To materialize the equivalent effect of an open sea in a limited space of a water tank, wave-absorption walls are required. These walls at the same time damp the free oscillations of the tank water.

A unit of the wave-absorption walls is shown in Fig. 8. This unit consists of a block made of thin vinylon ribbons (same material as described in 3.1) with a wooden frame ($2 \times 1 \times 0.2 \text{ m}^3$) and two metal nets. The density of these ribbons in the frame is experimentally adjusted to the right value. A method for testing these walls is shown in Fig. 9. The walls to be tested are put in a variable-length water tank, and the amplitude decay of the free oscillations caused by an exciter

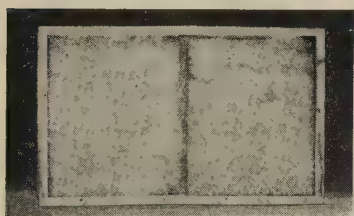


Fig. 8. Unit of the wave-absorption wall.

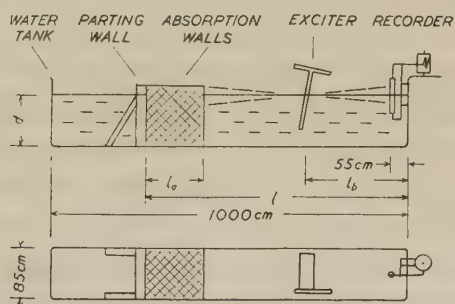


Fig. 9. Method of testing the wave-absorption walls.

is found by a water-level recorder. The walls were tested with various combinations of density of ribbons, thickness of walls, number of walls, distance between walls, and period and amplitude of oscillation. Some examples of the arrange-

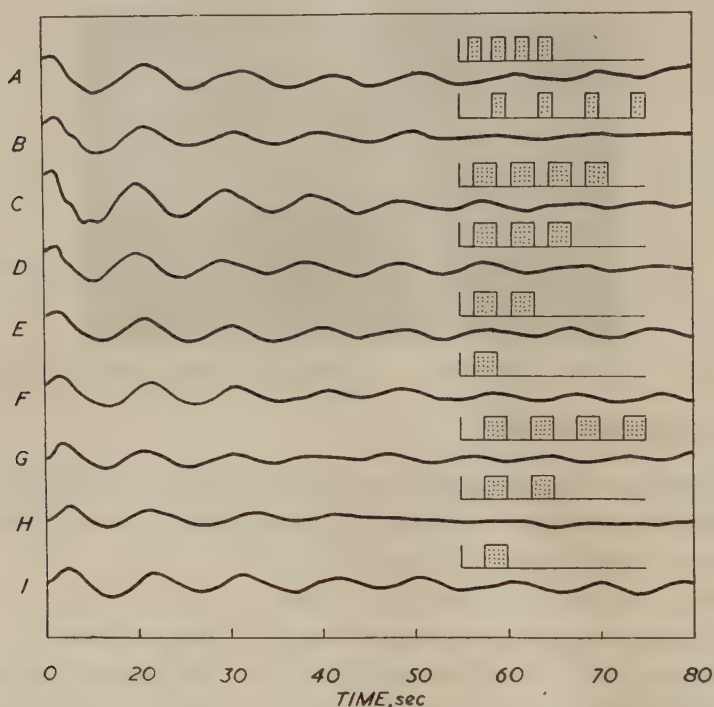


Fig. 10. Some example of the arrangements of the wave-absorption walls and the records of the tank-water oscillations.

ments of the walls and the records of the oscillation of the tank water are shown in Fig. 10. Some examples of the characteristics of the absorption walls are shown by the lines $\tan^{-1}(W_n/W_{n+1}) - \pi/2$ in Fig. 11, where W_n and W_{n+1} are the double amplitudes of the oscillation at the n and $(n+1)$ th peak respectively.

An arrangement of the wave-absorption walls in practical use in the present model experiment is shown Fig. 19 (5.2). In this arrangement, about twelve units of the walls are used. The effect of this arrangement was tested by comparing two responses caused by a sudden change of water level with the walls and without the walls. An example of the effect of the wave absorption is shown in Fig. 12.

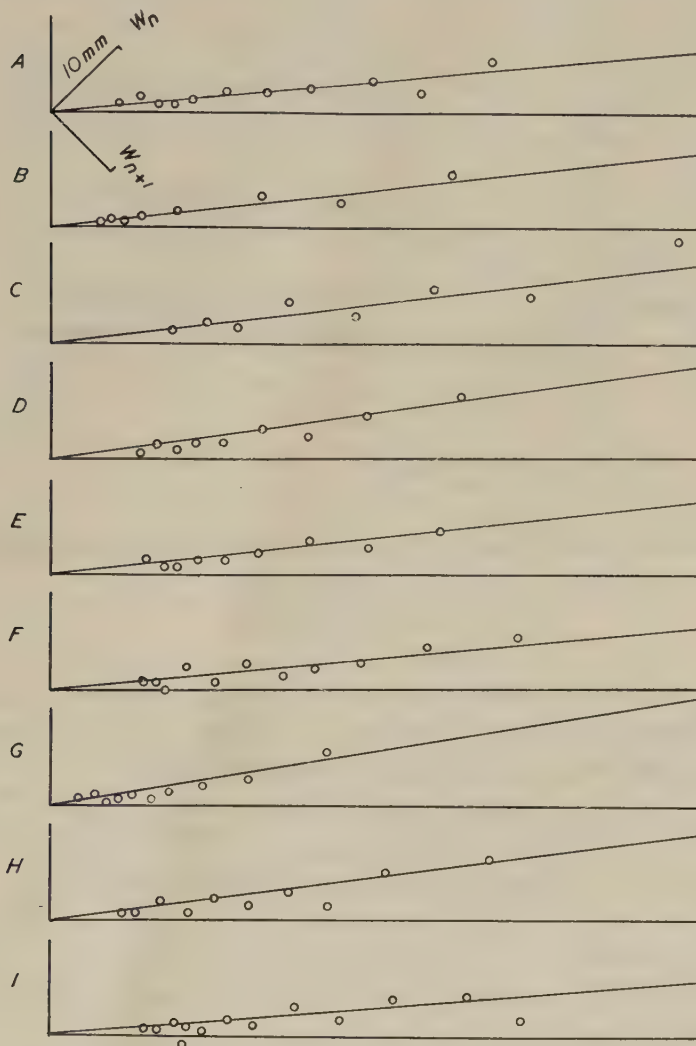


Fig. 11. Some examples of the characteristics of the wave-absorption walls shown in Fig. 10.

3.3 Note on a model including an oscillation system

When a prominent oscillation system, such as the bay described in 3.1, is included in a model, the error of the time reduction coefficient affects the amplitude of the oscillation in the model. The effect is important in designing both the model and the wave generator.

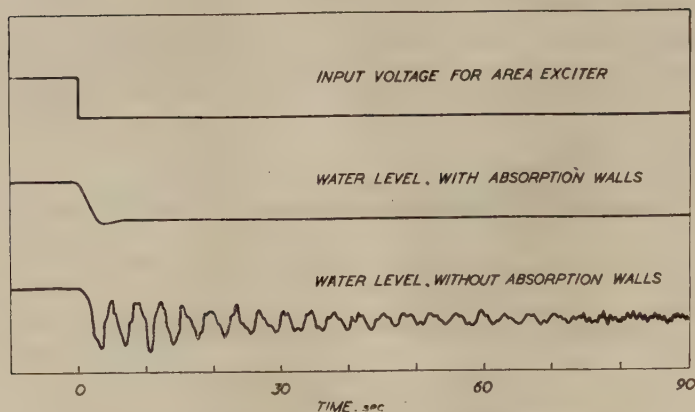


Fig. 12. Example of the effect of the wave-absorption walls in the proper tank.

The ratio of the amplitude of the oscillation to that of the external force is given by

$$v = \{ (1 - 1/u^2)^2 + 4h^2/u^2 \}^{-1/2}$$

$$u = T/T_0$$

where T_0 is the natural period of the system, T is the period of the force, and h is the damping constant of the system. If the period of the external force in the model has an error ΔT , the value of v becomes v' where:

$$v' = \{ (1 - 1/u'^2)^2 + 4h^2/u'^2 \}^{-1/2}$$

$$u' = (T + \Delta T)/T_0$$

If we define the error in the amplitude of the oscillation as

$$\varepsilon_v = v'/v - 1$$

this value is given by

$$\varepsilon_v = \{ (1 - 1/u^2)^2 + (2h/u)^2 \}^{1/2} [\{ 1 - 1/u^2(1 + \varepsilon_t)^2 \}^2 + \{ 2h/u(1 + \varepsilon_t) \}^2]^{-1/2} - 1$$

where $\varepsilon_t = \Delta T/T$.

The values of ε_v for $u = 0.2 \sim 1.8$, $h^2 = 0 \sim 0.16$, $\varepsilon_t = -0.2 \sim +0.2$ are shown in Fig. 13. For the present model shown in Fig. 6, h^2 is about 0.04, u is about 0.8 for the M_2 component of the tide. Then if $\varepsilon_v = 0.02$ is required, ε_t must be less than 0.005.

4. Time-function-voltage generators for the excitation

To excite the hydraulic model through electronic-mechanical devices, time-

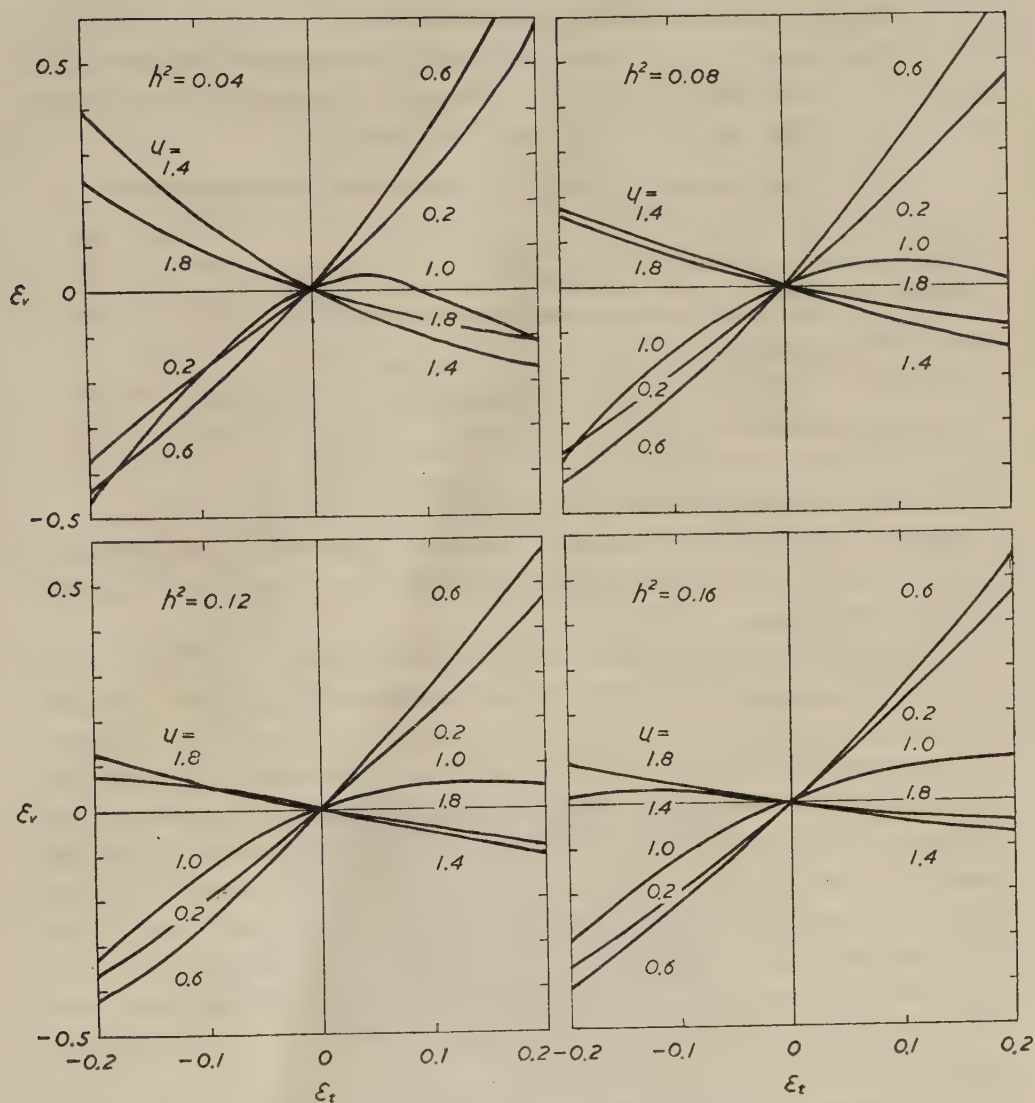


Fig. 13. Relation between the error in time, ε_t , and the error in the vertical displacement of the water-level, ε_v , in an oscillation system of a model.

function-voltage generators are required. These generators consist of a sine-wave-voltage generator, a square-wave-voltage generator, and an arbitrary-waveform-voltage generator.

4.1 Sine-wave- and square-wave-voltage generators

For these generators, a R-C wien-bridge oscillator, and a multi-vibrator circuit driven by the same oscillator are used. The circuit diagrams are shown in Fig. 3, and the principal specifications are shown in Table 1.

Table 1. Specifications of the sine-wave- and square-wave-voltage generators

Frequency range	0.01 to 1	c/s
Frequency deviation from scale of dial	within ± 5	%
Frequency fluctuation, under power-line-voltage fluctuation $\pm 10\%$	within ± 10	%
Output voltage, at 10 k-ohms load, pk-pk	1 to 10	V
Fluctuation of output levels, under power-line-voltage fluctuation $\pm 10\%$	within ± 0.2	db
Waveform distortion, in sine-wave	within ± 2	%

4.2 Arbitrary-waveform-voltage generator

This generator has been designed to reproduce electrically a curve drawn on the x - y axes of a chart, the magnification in the x and y directions being independent of each other.

The principle of the generator (ISHIGURO, 1954) is shown in Fig. 14. A chart (1) on which an arbitrary waveform (2) and time-marks (3) are drawn is shifted along the x -axis at a uniform speed V_1 by a synchronous motor (M_1). A tracer (4) connected with a contact needle (5) is driven by a controller (6) to follow the curve manually. A modulation roller (7) to which is attached an electric conductor (8) in the shape of a right-angled triangle (9) is rotated at a uniform speed V_2 by another motor (M_2). In this construction, an electric circuit consisting of (5) and (8) is broken at the same period as that of the rotation of the roller, and the time of contact is proportional to the y -co-ordinate of the curve (2). As the ratio of V_2 to V_1 is more than 100, a pulse-width-modulation which is independent of the absolute speed of the chart is obtained. The actual construction of the device is shown in Fig. 15.

To reproduce the same waveform voltage repeatedly, a doublechannel magnetic tape recorder is used. A 1 kc/s constant-amplitude voltage, which is pulse-width-modulated by the above device, is recorded on one channel of a magnetic tape. At the same time, pulses corresponding to time marks described on the edge of the chart in pencil (3) are recorded on the other channel of the same magnetic tape. This voltage is produced by a circuit from a 1 kc/s carrier-voltage line to

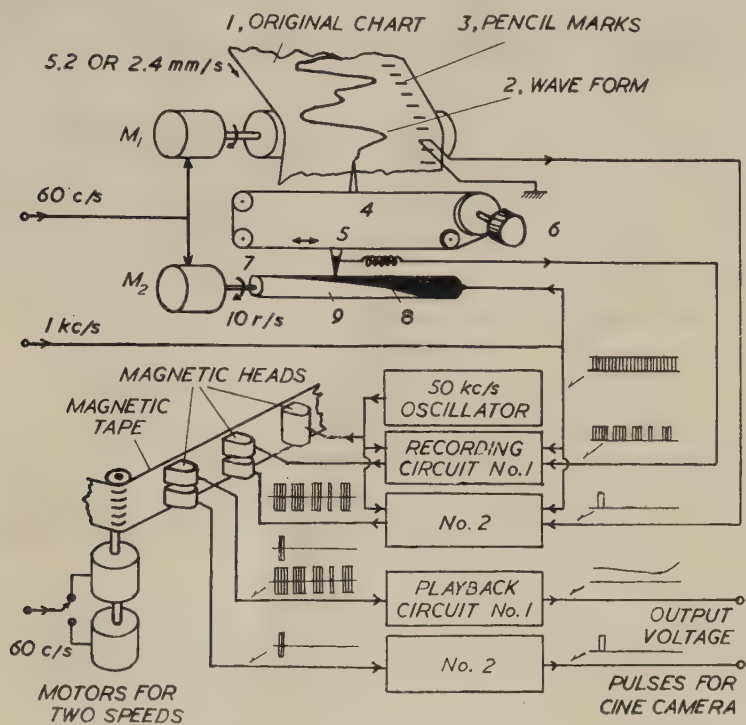


Fig. 14. Principle of the arbitrary-waveform-voltage generator.

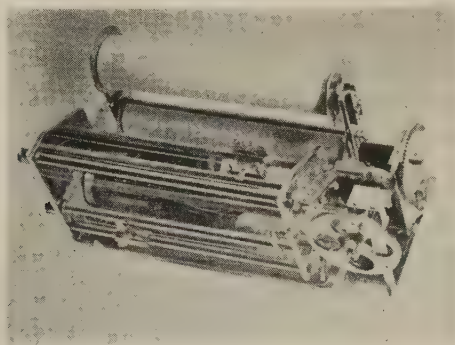


Fig. 15. Mechanical part of the arbitrary-waveform-voltage generator shown in Fig. 14.

the tape recorder circuit through two needle conductors which are usually in contact with the surface of the chart and make a circuit when the pencil time-

marks on the chart pass under the needles. When the magnetic tape is played back, the output voltages of both the channels are demodulated by two independent demodulators.

When an original waveform is transferred into a magnetic tape, a suitable chart speed for tracing the curve has to be chosen. When the tape is played back, however, a suitable speed for the time reduction of the model is required. To satisfy these conditions, both the chart speed and the tape speed are designed to be variable. The relation between these and the time reduction of the model is given by (the definitions of the symbols are shown in 3.1 and Table 2)

$$nC = S_a (K_i/K_r)$$

Bearing in mind the conditions of the hydraulic model design, the mechanical construction of the devices, and the electronic circuit, the following values have been chosen for the present equipment as shown Table 2. The number of revolutions per second of the modulation roller is 10, therefore the frequency of modulation pulse is also 10 c/s. The principal specifications of the magnetic tape recorder are also shown in Table 2.

Table 2. Specifications of the arbitrary-waveform-voltage generator.

Original chart, effective width	250	mm
scale of y-axis (time axis), S_a		
for standard chart	15	mm/hr
for chart of Kelvin type predictor	20/3	mm/hr
circumference of roller, C	1875/12	mm
number of revolutions of roller, n	2	rev/min
Magnetic tape, width	6.35	mm
ratio of recording and play-back speed, K_r	2	
duration of play-back, at speed of 38.1 cm/sec	20	min
deviation of speed	within ± 0.3	%
flutter and wow, RMS	within $\pm .25$	%
Output voltage, maximum	2	V
range of component period	1~1200	sec

The diagram of the recording and playback circuits are shown in Fig. 3. An integrating circuit consisting of Germanium diode (1T23) rectifier and a R-C network is used as a demodulator of the arbitrary waveform voltage. Two relay circuit including electronic tubes are independently used to record and play back the time-mark voltage. This output can operate a heavy-duty and high-speed switch by which a cine-camera (see 6.2) is driven.

The overall characteristic which is the relation between the displacement on the chart and the output voltage of the playback circuit of the magnetic recorder is shown in Fig. 16.

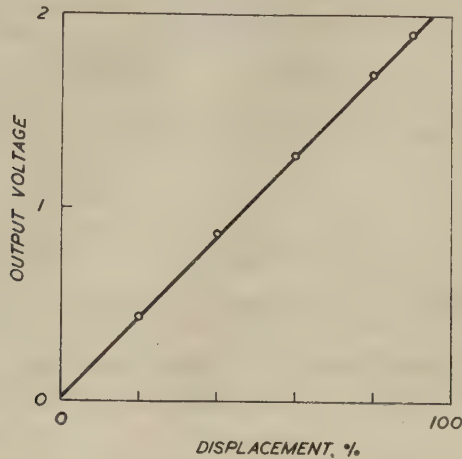


Fig. 16. Overall characteristics of the arbitrary-waveform-voltage generator. Relation between the displacement on the y-axis of the chart and the output voltage of the playback circuit of the magnetic tape recorder.

5. *Excitation generator*

To give an excitation to the hydraulic model by transferring the voltage from the function generator into a displacement of the water-level of the model, an electronic-magnetical-hydraulic servo system is used. A simplified diagram of the system is shown in Fig. 17.

Two kinds of exciters are prepared for the present equipment. One of them, called 'point exciter' is used to give an excitation to a point on the model, and another one, called 'area exciter', to an area on the model. Any one of them can be driven by an electronic circuit through a selector-switch.

5.1 *Point exciter*

This consists of a movable block which is partly immersed in the water and is driven by a cam connected with an electric servo motor. The mechanical displacement of the cam is electrically fed back into the input of the electronic

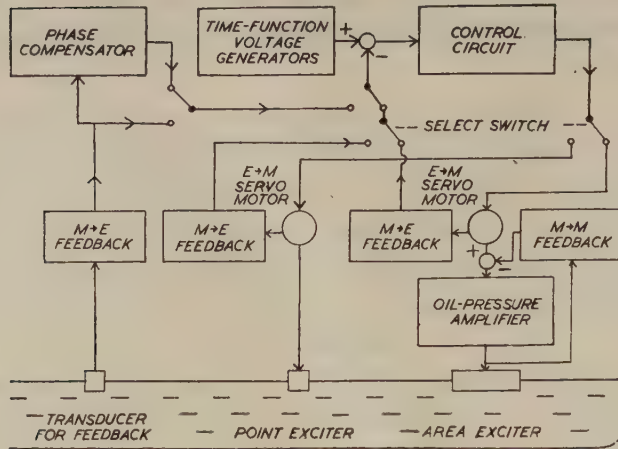


Fig. 17. Simplified diagram of the excitation generator. *E* shows the electronic system, and *M* shows the mechanical system.

control circuit through a potentiometer connected with the cam. At the same time, the water level variation near the movable block is also electrically fed back into the same input through an electronic water-level transducer (same construction as that of the response recorder, see 6.1) and a phase compensating circuit. The size of the movable block and the distance between the block and the feedback transducer are adjusted to be suitable for the problem. As the size of this exciter including the feedback transducer is small, it is possible to set it at any position on the model. The circuit is shown in Fig. 3.

5.2 Area exciter

Although this exciter is the same in principle as the point exciter, the actual construction is different, because a bigger size of movable block and therefore a larger power is required.

The construction of the movable block and the associated parts are shown in Fig. 18. The block is hung by a shaft with two capstan rollers, chains, and a counter weight. The shaft is supported by two supports which are set one on each side of the water tank and can be shifted if necessary. The movable block is controlled by an electric servomotor working through an oil-pressure amplifier to obtain the necessary mechanical output power.

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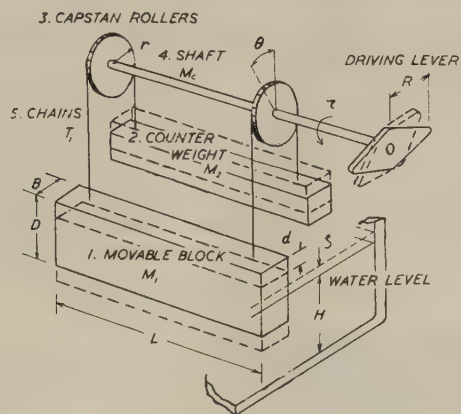


Fig. 18. Schematic diagram of the area exciter.

Table 3. Specifications of the area exciter

Estimated maximum area to be controlled, A	1.7×10^5	cm^2
Movable block, length, L	320	cm
width, B	52	cm
height, D	50	cm
reserved height, d_r	10	cm
maximum immersed height into water	40	cm
controllable water mass	5×10^6	cm^3
mass, M_1	680	kg
Counter weight, mass, M_2	265	kg
Capstan rollers, effective radii, r	22	cm
mass including assemblies, M_c	50×2	kg
Main shaft, length	400	cm
span between supporting points	334	cm
mass	233	kg
Effective length of driving lever (adjustable), R	15/18/21/24	cm
Maximum output torque of oil-pressure amplifier	90	kg-m

	Max.	Neutral	Min.	Without water	
Rotation angle of shaft, θ	31.5	0	-31.5	-44.0	degrees
Displacement of movable block, d	11.0	0	-11.0	-15.0	cm
Displacement of water-level, ζ	-0.6	0	0.6	—	cm
Bouyancy of movable block, F_b	609	416	222	0	kg-wt
Tension of chain for movable block, T_1	61	264	458	680	kg-wt
Torque to drive shaft, τ	-39	-0.2	38.6	83	kg-wt-m
Load at supporting points of shaft, F_1	1029	1171	1416	1638	kg-wt

The dimensions of the movable block are given by (the definitions of the symbols are shown in Fig. 18 and Table 3)

$$B = A / (d/\zeta + 2) L$$

$$d = \pi r / 180$$

$$D = 2 (d_{max} + \zeta_{max} + d_r)$$

The mass of movable block and that of the counter weight are given respectively by

$$M_1 = (D/2 + d_{max} - \zeta_{max}) LB\rho + M_r$$

$$M_2 = M_1 - DLB\rho/2$$

where ρ is the density of water. The buoyancy of the movable block is given by

$$F_b = (D/2 + d - \zeta) LB\rho g$$

The tensions in the chains supporting the movable block and the counter weight are given respectively by

$$T_1 = M_1 g - F_b$$

$$T_2 = M_2 g$$

The torque required to drive the shaft is given by

$$\tau = \{ (M_1 - M_2) g - F_b \} r$$

The maximum speed of the movable block in the upward direction depends on the oil-pressure amplifier, but that in the down-ward direction depends on the acceleration of gravity, i.e. the time from the beginning of the downward motion to any particular instant. The following condition, therefore, is given

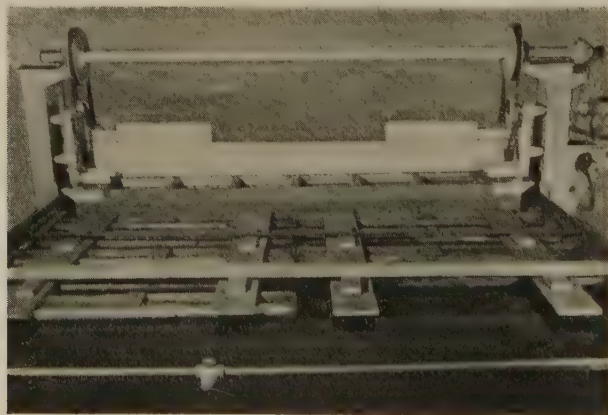


Fig. 19. Area exciter and the wave-absorption walls.

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$$2d_{max} \left\{ \frac{2(M_1 - M_2)r^2 + M_0r_0 + M_0r_s}{(M_1 - M_2)r^2 g} \right\} < P_{min}^2$$

where r_0 and r_s are the ratio of gyration of the capstan rollers and that of the main shaft respectively, and P_{min} is the minimum period to be operated.

The specifications of this device including the figures obtained by using the above equations are shown in Table 3. The actual device is shown in Fig. 19.

The oil-pressure amplifier system which is set between the electric servomotor and the movable block is shown in Fig. 20. The cam (1) connected with the

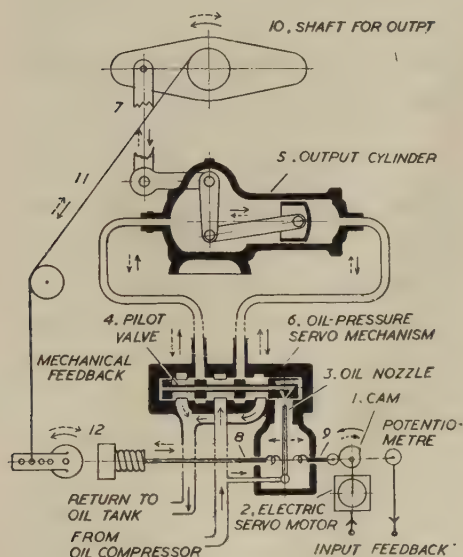


Fig. 20. (Left) Schematic diagram of the oil-pressure amplifier with a feedback mechanism.

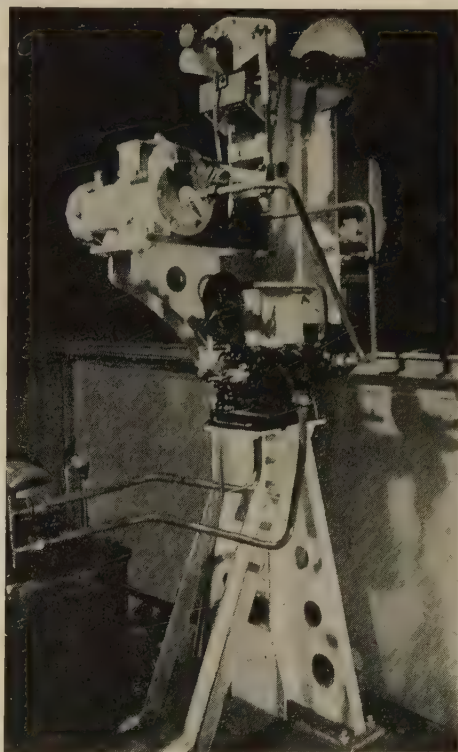


Fig. 21. (Right) Oil-pressure amplifier and a part of the area exciter.

electric servomotor (2) controls the position of the top of a nozzle (3) through which compressed oil is coming out in a jet. A pilot valve (4), by which the main output cylinder (5) is controlled, follows the position of the jet by an oil-pressure servo mechanism (6). The movement of the piston of the main output cylinder is transmitted to the movable block through a lever system (7). The movement of the block is mechanically fed back to mechanical input of the nozzle

(8), in reverse phase to the input from the electric servomotor (9), through the shaft (10), a flexible wire (11), and a screw-micrometer-like mechanism (12). At the same time, the movement of the shaft of the servomotor (2) is electrically fed back to the electronic control circuit through a potentiometer, and the water-level variation caused by the movable block is also fed back to the electronic control circuit through an electronic water-level transducer and the phase compensator (see Fig. 17).

The actual device is shown in Fig. 21. The circuit diagram is shown in Fig. 3.

6. Response recorders

To record a water-level variation which is a response caused by an excitation on the model, an electronic and an optical method are used.

6.1 Electronic water-level recorders

This method is used to record the water-level variations on several points on the model simultaneously by a simple procedure.

The principle of this method is shown in Fig. 22(a). A cylinder (1), of which the sectional area is uniform and the length is slightly longer than the maximum water-level variation to be measured, is supported by two elastic levers

Table 4. Specifications of the electronic water-level recorder

Minimum measurable water area	about 1	cm ²
Maximum range of water-level variation	±15	mm
Period range of water-level variation	∞~0.5	sec
Cylinder, length	40	mm
diameter	8	mm
weight	10	g
Maximum displacement of moving part of transducer for maximum water-level range	±0.25	mm
Input carrier voltage of transducer, stabilized	6.5	V
Maximum output voltage of transducer, in push-pull	0.5	V
Extension lines (4 conductors) of transducer	about 10	m
Maximum output current of demodulator at 1.5 k-ohms load, DC, push-pull	±40	mA
Ink-writing oscillograph, pen travel	±20	mm
static deviation	±0.2	%
frequency response, 0~30 c/s	within ±2	%
sensitivity	0.5	mm/mA
chart speeds	1, 15, 30, 60, 120	mm/sec or mm/min
chart-speed fluctuation	within ±0.3	%

(2). When the cylinder is partly immersed in the water, the bouyancy effect on the cylinder is balanced by a force which is caused by a small displacement of the elastic lever. This displacement, i.e. the displacement of the cylinder, is measured by electronic circuit. In this method, it is easy to arrange that the natural period of the moving part is very much shorter than the period of the water-level variation on the model, and to obtain a satisfactory dynamic characteristic (ISHIGURO, 1957). The cylinder is made of a waterproof material, and is covered by a thin blotting-paper to keep the cylinder surface wet, when in use, to obviate errors caused by the surface tension of water.

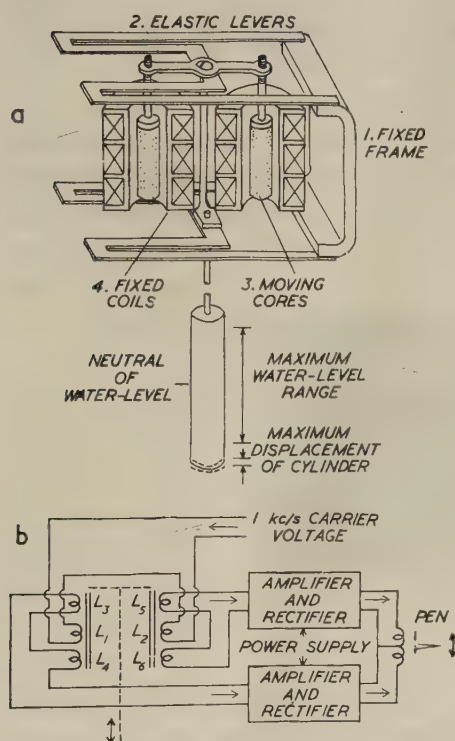


Fig. 22. Principle of the electronic water-level recorder.

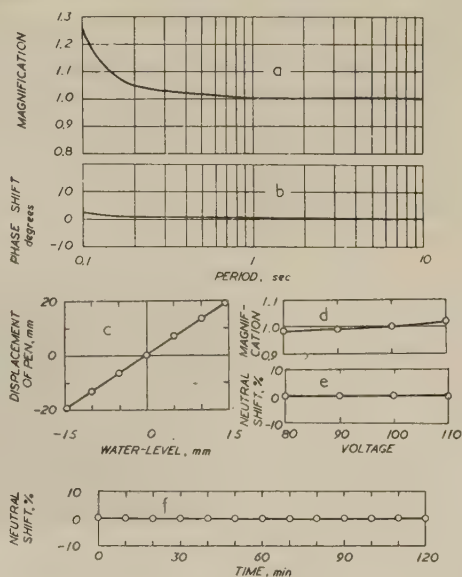


Fig. 23. Overall characteristics of the electronic water-level recorder. (a) and (b) Frequency response. (c) Static linearity. (d) and (e) Stability against the powerline voltage. (f) Stability under running condition.

To measure the displacement of the cylinder, two moving cores (3), connected with it, and two groups of fixed coils (4), each one consisting of three coils, are used. A simplified circuit diagram including these cores and coils is

shown in Fig. 22(b). A 1 kc/s carrier voltage from a stabilized-amplitude oscillator is supplied to the coils L_1 and L_2 which are set in the middle of each group. When the cylinder is in a neutral position, the voltages picked up in coils L_3 and L_4 , and L_5 and L_6 cancel out but when the cylinder is displaced, the out of balance voltages develop across the coils L_3 - L_4 and L_5 - L_6 in a push-pull form and are amplified with a common power-supply, and drive a push-pull type ink-writing oscillograph. The details of the circuit are shown in Fig. 3. In this arrangement, the measurement is sensibly independent of the variation of laboratory conditions, including the voltage fluctuation of the power supply.

The principal specifications of this method are shown in Table 4. The overall frequency response is shown by the variation of the magnification and the phase shift between the water-level variation and its record in Figs. 23(a) and (b). The static relation between the water-level and its record is shown in Fig. 23(c). The variation of the magnification and the fluctuation of the neutral position against the fluctuation of the power-line voltage are shown in Figs. 23(d) and (e). The stability of the neutral position under running conditions for two hours is shown in Fig. 23(f).

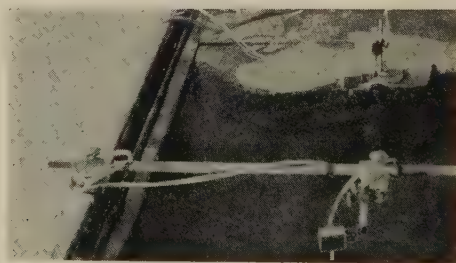


Fig. 24. Transducers of the electronic water-level recorder with two types of holders.

The transducer, in which the cylinder, the elastic levers, the coils and the cores are contained, is supported by an adjustable holder to fix it on the model. Two types of transducer holders are used as shown in Fig. 24. One is for use near a shore of the model, and consists of a screw-micrometer-like vertical adjuster and a simple horizontal adjuster. The other is used for a wider water surface of the tank, and consists of the same type vertical adjuster and a horizontal adjuster fixed in two rails which are set on the tank walls.

For the present equipment, six transducers with the associated devices and a 6-channel ink-writing oscillograph are used.

6.2 Optical water-level recorder

This method records photographically the level variation of the whole water surface of the model and does not disturb the model in doing so;

The principle of the method is shown in Fig. 25(a). An image of a mesh (or a group of spots) is projected, at an incident angle of less than 45 degrees, on the water surface of the model in a dark room; From the geometrical relation between the two points where the light beam cuts the undisturbed water surface and the disturbed surface, a relation

$$\Delta Z = H (\Delta l / l)$$

is obtained. The definitions of the above symbols are given in Fig. 25. Although the light is projected obliquely on the water surface, it is possible to focus the image on the surface, by using a specially designed optical system and by scattering white powder or aluminium powder on the surface. Then, if the distribution of Δl is recorded by a cine-camera facing normally to the water surface, the distribution of ΔZ can be worked out.

This transformation in practice is easily carried out by using a scale shown in Fig. 25(b). The design of this scale is self-evident, where K_s is a coefficient between the scale of the model and that of a diagram on which the record is enlarged. The scale is engraved on a transparent plate. If the scale is put on the diagram so as to superpose the pin-hole S on the corresponding position of the light source of the projector on the water surface, and superposing P_s and P_m on the record of the points where the light beam crosses the undisturbed and the disturbed water surface respectively, then the reading of P on the ΔZ scale gives the value of ΔZ . It will be more convenient to graduate the ΔZ scale in actual units using K_s (see 3.1).

Although the magnification is given by

$$K_m = \Delta l / \Delta Z = l / H$$

so that the larger l the better the accuracy, the values of l and H are in practice limited by the lack of uniformity of the illumination of the image on the water surface. A range of $l=100\sim 400$ cm, $H=4\sim 15$ cm, and therefore $K_m=25\sim 50$ will be suitable for ordinary cases.

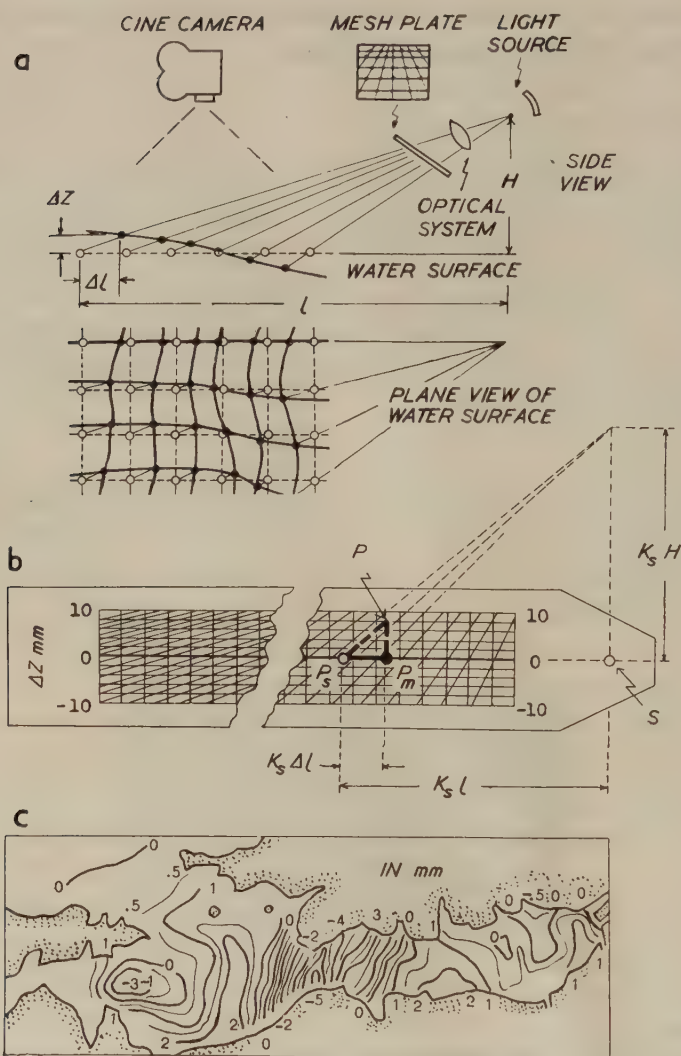


Fig. 25. (a) Principle of the optical water-level recorder. (b) Principle of the scale for analysing the optical records. (c) Example of the record obtained by the optical method.

An area which can be covered by one projector is limited, if the recording area is larger than this, more than one projector has to be used. For the present equipment, six projectors are prepared.

The overall accuracy of this method depends mainly on the resolving power

of the camera and films used for recording. Assuming that the resolving power including that of the photographic procedure is 50 lines/mm, the dimension of the area to be recorded is $3.5 \times 2.5 \text{ m}^2$ (see the rectangle a-b-c-d in Fig. 6), and the value of K_m is 30, an example of the values used in the design of this method is shown in Table 5.

Table 5. Estimation of the accuracy of the optical water-level recording method related to the size of the camera frame

Camera	Dimension of film frame	Ratio of recorded area to film frame	Measurable minimum length on water surface (mm)	Measurable minimum displacement of water-level (mm)
16-mm	10.41×4.75	300	15.0	0.50
35-mm	20.05×16.03	125	6.25	0.28
Leica-size	35.03×22.05	85	4.15	0.14

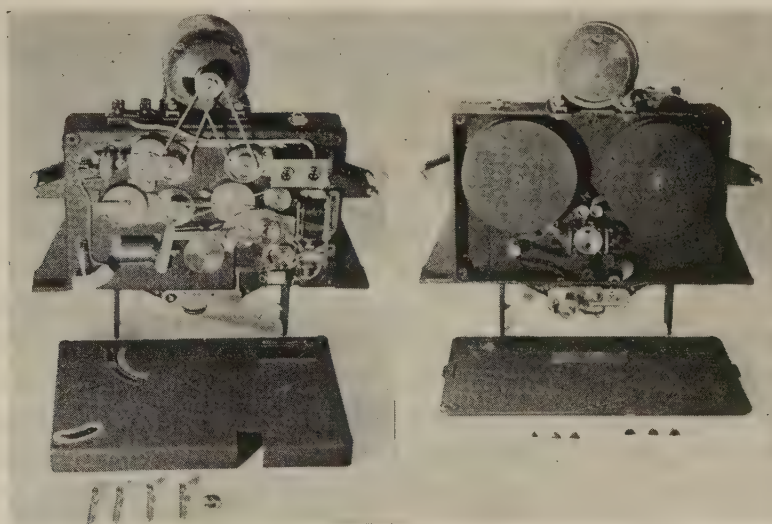


Fig. 26. Cine-camera used for the optical water-level recording.

For the present equipment, a specially designed 'Leica-size' cine-camera as shown in Fig. 26 is used. The optical system of the camera, 'Canon V-T' with a 60° -wide-angle lens is used. The actions of the exposure and the film transport of this camera are carried out by an electric motor working through a mechanism consisting of cams, gears and electromagnetic plungers. The plunger circuits are controlled by manual operation or by a magnetic-tape recorder through an

electronic circuit, and can be operated at any regular or irregular time interval greater than about 0.5 sec. Therefore, the instants at which the hydraulic model is photographed can be prearranged to correspond with the original time function of the excitation, by making time marks in pencil on the edge of the time-function chart (see Fig. 14). The circuit diagram of the camera control system is shown in Fig. 3.

7. Associated devices

Stabilized 1 kc/s oscillator

To transmit several very-low-frequency signals in the electronic circuits of the equipment, an amplitude-modulated carrier-voltage system is used, incorporating an oscillator of which the output voltage (6.5 volts) and the frequency (1 kc/s) are stabilized. The circuit diagram of the oscillator is shown in Fig. 3. The fluctuation of the output voltage is within $\pm 1\%$ under a load impedance variation of $\pm 80\%$, or a power-line-voltage variation of 80~110 volts, and for two hour running.

Frequency stabilized 60 c/s oscillator

In a case where the coefficient of the time reduction of the hydraulic model, especially with an oscillation system (see 3.3), is not small, the speeds of both the input and the output chart and that of the magnetic tape (see 4.2) should be very accurate. To keep these speeds constant, the synchronous motors connected with these devices are driven by a frequency stabilized power supply. The circuit diagram of this power supply is shown in Fig. 3. As a frequency standard an electro-magnetic tuning fork made of elinvar of which the temperature coefficient is less than $+1.5 \times 10^{-5}$ is used. The frequency is kept within 60 ± 0.001 c/s. The output voltage of this device is also stabilized sufficiently for this purpose by a feedback circuit, and a power of about 150 watts at 100 volts is obtained.

Time standard receiver

To check the absolute value of the above speeds independently, a radio receiver, tuned to several national standard time signals, is built in the equipment, and connected with the time-mark circuit and a clock. The circuit is shown in Fig. 3.

Power-supply-voltage stabilizers

To stabilize the main electronic circuits of the equipment, two voltage-stabilizing circuits are used between the equipment and a power source line. Their circuits are shown in Fig. 3, and the connections with the other devices are shown in Fig. 2. One of them consists of a magnetic amplifier, and is used for the devices which require a higher stability. The output-voltage fluctuation of this stabilizer is $\pm 0.3\%$ with source-line fluctuations of $\pm 20\%$ in the voltage and $\pm 5\%$ in the frequency. The other one consists of two ferro-resonance circuits, and is used for the devices which do not require so high a stability. The output-voltage fluctuations of these circuits are $\pm 2\%$ under source-line fluctuations of $\pm 20\%$ in voltage and $\pm 1.6\%$ in frequency.

Oil compressor

To operate the oil-pressure amplifier (see 5.2) an oil compressor driven by an 200-volts 3-phase 2-HP electric motor is used. Delivery of the pump is about 40 litres/min maximum, and the pressure is regulated by a spring-balanced valve to keep usually at about 4 kg/cm².

Cabinet for the electronic devices

The main parts of the electronic devices of the equipment are built in a rocking type steel cabinet as shown in Fig. 5. For the ventilation of these devices, an electric motor fan is set on the top of the cabinet. To protect these devices from moisture when not in use, the whole body of the cabinet is shielded by a cover made of vynil with several packing levers set on the bottom. The weight of the cabinet including all the equipment is about 1,000 kg.

8. Overall characteristics

Overall characteristics of the present equipment are shown in Table 6. The accuracies shown in this table do not include those of the similarity of a hydraulic model itself. Examples of the records representing the overall characteristics are shown in Figs. 27 and 28.

About 2k-watts of 60c/s, single phase, 100 volts, and also about 2k-watts of 60c/s, three phase, 200 volts electric power supplies are required to operate about 120 electronic tubes and 8 electric motors used for this equipment.

Table 6. Overall characteristics (sine-wave) of the equipment

		Amplitude range (mm)	Accuracy in amplitude (%)	Period range within $\pm 5^\circ$ phase shift (s)
Excitation	Point exciter	± 15	± 3	1~100
	Area exciter	± 120	± 5	5~100
Response	Electronic recording	± 15	± 2	0.5~
	Optical recording	± 15	± 2	5~

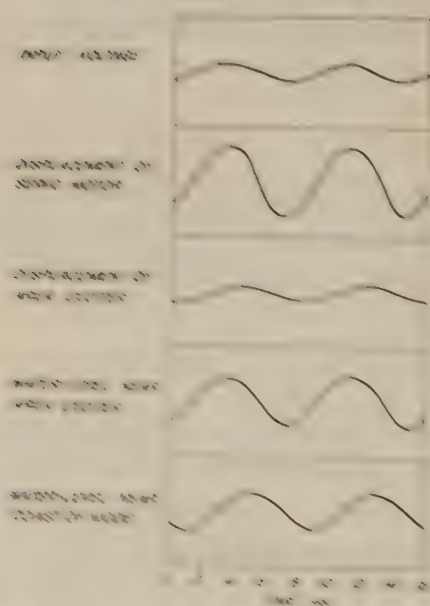


Fig. 27. Example of the record showing the overall characteristics of the equipment (sine-wave).

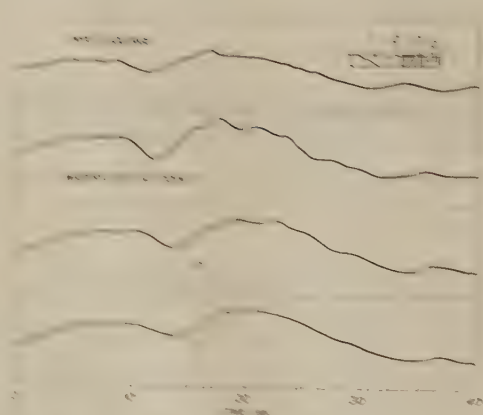


Fig. 28. Example of the record showing the overall characteristics of the equipment (sine-wave).

9. Conclusions

An experimental method of analysis for long-wave phenomena in the ocean, combining a hydraulic model technique with some electronic techniques, has been obtained. It has the strong points of both the techniques, i. e. flexibility of the former to represent arbitrary bottom topographies and of the latter to represent arbitrary time functions. This method is being applied successfully to a practical

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problem of coastal engineering, and may be for other similar problems and for oceanographical and hydraulic problems.

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The author wishes to express his thanks to Prof. K. Hidaka, Prof. M. Uda, and Dr. M. Nakano for their constant encouragement. The author also wishes to express his thanks to Mr. A. Fujiki, Mr. M. Nagata, Mr. S. Morikawa, and Mr. H. Kimura for their able assistance in building up the equipment and Mr. M. Hayashida for their kind help in preparing this paper.

The cine-camera shown in Fig. 26 was designed specially for the author's specifications by Mr. G. Nishimura of the Konan Camera Laboratory.

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Note

In this paper, the description of the equipment refers to the position at the end of 1956. Since January 1957, work on the application of this method to some practical problems, and some improvements in the characteristics of the equipment, have been carried out mainly by Mr. A. Fujiki, and the results of this work will be published by him separately.

An Investigation on Meteorological Tides in the Neighbouring Seas of Japan (IV): General Features of Regional Distribution and Seasonal Variation.

By

Sanae UNOKI

Meteorological Research Institute, Tokyo

Abstract: The purpose of this paper is to describe statistically the features of regional distribution and seasonal variation of meteorological tides on various coasts of Japan because our knowledge of them is very fragmentary in comparison with that of astronomical tides. As a measure representing the characteristic strength of meteorological tides, the maximums of positive and negative anomalies of sea level in each month are used.

1. Preface

As is commonly known, the actual tide consists of astronomical tides and meteorological ones. The former, being due to the attraction of the moon and the sun, has been investigated in detail practically as well as theoretically, and our knowledge of it is considerably rich. On the other hand, the latter has not been investigated so much for the reason that it is usually more feeble and more unsteady than the former. In our country, however, storm tides corresponding to the most conspicuous phenomenon of meteorological tides sometimes reach the height of two or three meters above usual sea level, and we have often suffered great damages by them since ancient times. Therefore, in order to understand the behavior of unusual storm tides well, it is naturally demanded to make clear the mean state of meteorological tides.

In this paper the features of regional distribution and seasonal variation of them are described statistically, and the actual state of storm tides due to typhoons and cyclones will be discussed in the near future. Moreover, it must be taken into consideration that the anomaly *above* predicted sea level or the *positive* anomaly has been noticed in some degree, but the anomaly *below* predicted sea level or the *negative* anomaly has seldom been investigated. Then the latter will be described as well as the former.

2. Observed data

The localities of forty-three tidal stations are represented in Fig. 1. The period of data differs for respective stations, that is, for six stations it is twenty-three years which is the longest, and for three stations two years.

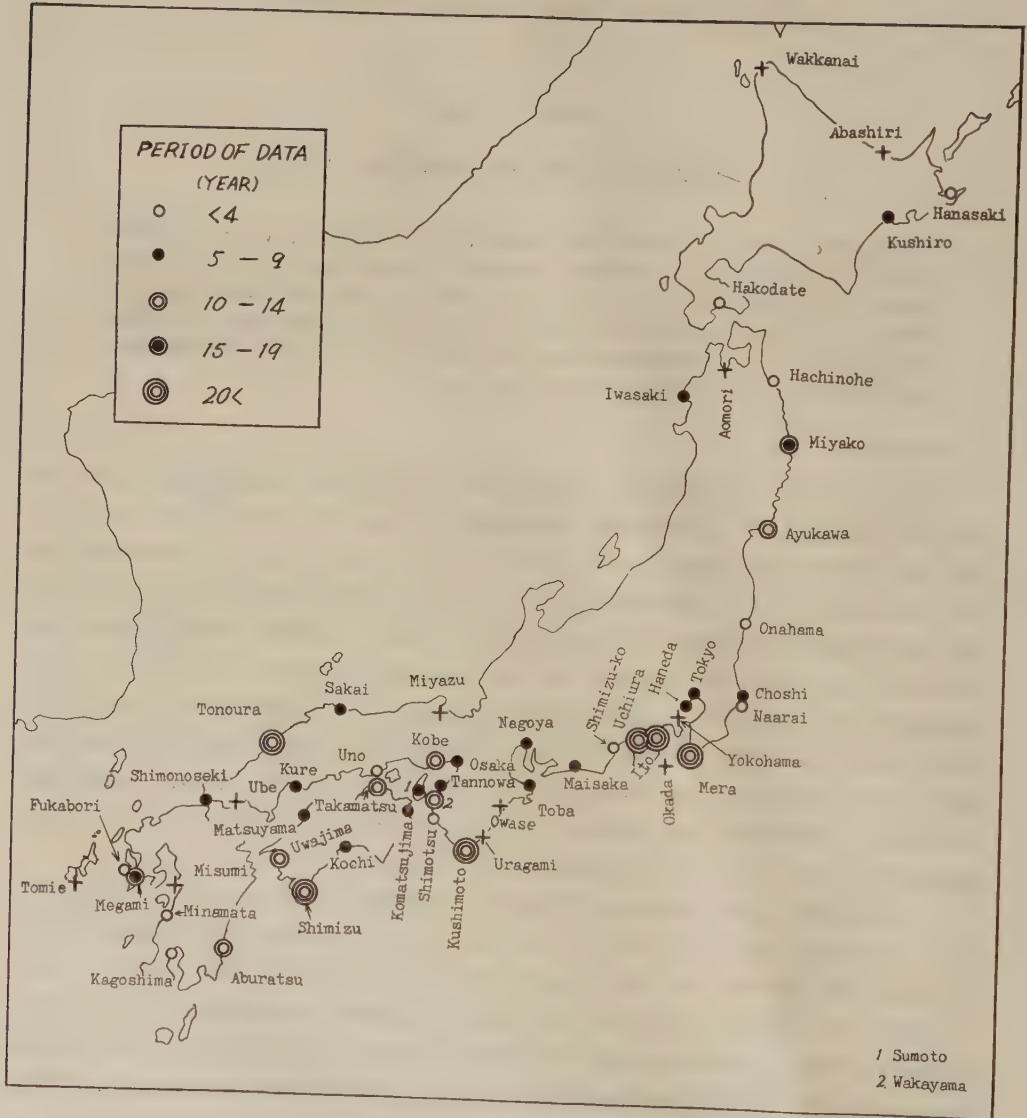


Fig. 1 Localities of tidal stations and period of data.

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Table 1. Monthly mean of the maximum of positive anomaly above predicted sea-level (in cm).

Station	Period	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Hanasaki	1956-58	26	45	39	21	21	17	12	24	28	22	21	25	25
Kushiro	1952-58	29	31	28	23	29	18	20	25	33	26	24	25	26
Hakodate	1955-58	26	24	23	22	20	14	15	17	23	25	21	29	22
Hachinohe	1957-58	21	25	31	18	19	16	17	18	31	28	21	36	23
Miyako	1942-58	13	21	24	23	18	16	15	16	22	20	21	26	20
Ayukawa	1949-58	19	22	22	22	19	16	16	15	21	23	21	23	20
Onahama	1956-58	18	26	25	16	19	17	14	11	31	22	18	23	20
*Choshi	1947-53	32	33	27	32	33	28	19	21	25	43	56	34	(32)
Naarai	1955-58	21	29	25	21	18	18	18	16	16	29	21	31	22
Mera	1936-58	23	24	25	25	20	20	23	26	30	30	24	26	25
Tokyo	1950-58	31	34	35	32	34	26	38	33	45	38	27	38	34
Haneda	1936-42	38	36	41	52	50	43	34	34	46	46	55	45	43
Ito	1936-58	22	23	22	24	20	22	20	22	25	25	23	25	23
Uchiura	1936-58	26	26	26	25	23	21	22	25	30	32	27	30	26
*Maisaka	1942-50	40	41	35	37	51	42	39	38	61	51	45	40	(43)
Nagoya	1951-58	34	30	27	31	34	26	27	38	52	47	34	37	35
Toba	1950-58	26	27	30	27	27	22	23	26	42	31	27	29	28
Kushimoto	1936-58	26	27	24	22	24	23	22	28	39	32	25	23	26
Shimotsu	1948-50	33	30	27	30	33	25	25	24	73	34	39	39	34
Wakayama	1949-58	29	28	30	28	30	28	25	35	48	37	29	30	31
Tannowa	1954-58	25	27	22	23	23	24	19	33	53	25	24	30	28
Osaka	1950-58	38	36	41	34	35	39	27	36	70	40	30	39	39
Kobe	1947-58	31	33	32	34	30	37	26	33	52	37	28	35	34
Sumoto	1952-58	28	26	25	24	31	27	21	30	36	28	25	29	28
Uno	1957-58	29	27	29	25	25	23	17	27	29	27	20	42	27
Kure	1951-58	36	32	34	35	29	31	30	32	61	49	34	36	37
Komatsujima	1953-58	25	27	23	24	25	22	18	37	34	25	21	30	26
Takamatsu	1949-58	32	32	35	30	28	28	26	35	47	38	27	35	33
Matsuyama	1950-58	28	27	31	25	23	22	21	23	52	42	26	33	30
Uwajima	1949-58	23	27	28	20	23	20	19	24	40	29	27	25	25
Shimizu	1936-58	24	23	23	21	22	22	25	25	37	31	24	26	25
Kochi	1950-58	23	19	23	19	20	22	27	29	36	32	22	23	25
Aburatsu	1946-58	19	20	20	20	19	19	31	28	32	28	21	21	23
*Minamata	1951-53	26	20	23	23	24	23	26	29	28	27	—	36	(26)
Megami	1936-58	25	27	26	23	22	19	24	31	28	23	22	25	25
Fukabori	1957-58	21	19	23	18	18	24	20	30	19	17	17	22	20
Shimonoseki	1953-58	21	23	27	27	25	24	23	36	41	23	19	31	27
Tonoura	1936-58	24	22	26	25	19	18	20	19	24	21	20	29	22
Sakai	1951-58	23	25	25	21	21	16	19	22	26	23	23	27	22
Iwasaki	1951-58	34	30	26	30	26	20	23	27	37	28	27	28	28
Chichi-jima	1942-43	19	19	14	20	14	14	11	12	15	16	14	18	15

* The accuracy of data is not satisfactory.

Table 2. Monthly mean of the maximum of negative anomaly below predicted sea-level (in cm).

Station	Period	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Hanasaki	1956-58	20	26	34	17	15	15	<i>13</i>	15	17	21	16	22	19
Kushiro	1952-58	20	20	22	20	19	<i>14</i>	18	20	24	18	22	20	20
Hakodate	1955-58	18	22	18	17	16	13	<i>11</i>	15	15	20	17	19	17
Hachinohe	1957-58	20	19	18	<i>14</i>	16	15	15	15	19	23	21	22	18
Miyako	1942-58	20	18	17	17	14	<i>14</i>	<i>14</i>	15	17	17	18	20	17
Ayukawa	1949-58	16	17	18	14	16	16	14	<i>14</i>	15	18	17	16	16
Onahama	1956-58	16	18	18	16	15	<i>11</i>	13	14	15	15	15	17	15
*Choshi	1947-53	24	27	25	26	25	19	<i>15</i>	28	18	26	28	29	(24)
Naarai	1955-58	23	22	21	19	19	17	<i>17</i>	18	19	21	21	20	20
Mera	1936-58	20	20	17	20	18	<i>17</i>	18	18	18	21	20	21	19
Tokyo	1950-58	25	26	28	26	23	<i>20</i>	22	21	25	30	25	27	25
Haneda	1936-42	40	38	48	51	35	32	32	34	48	36	<i>31</i>	42	39
Ito	1936-58	22	22	19	22	22	<i>17</i>	17	17	17	21	20	22	20
Uchiura	1936-58	25	24	23	22	21	20	<i>19</i>	20	21	23	22	26	22
*Maisaka	1942-50	36	35	<i>31</i>	34	34	37	34	36	37	39	40	40	(36)
Nagoya	1951-58	25	22	25	22	23	21	20	<i>20</i>	25	27	28	29	24
Toba	1950-58	18	18	21	20	20	19	19	18	20	20	18	22	19
Kushimoto	1936-58	19	18	19	23	18	18	<i>17</i>	18	21	21	24	20	20
Shimotsu	1948-50	21	22	34	<i>18</i>	28	27	25	28	23	21	22	34	25
Wakayama	1949-58	24	24	24	26	22	23	23	24	24	24	23	26	24
Tannowa	1954-58	21	21	19	21	20	19	<i>18</i>	20	19	19	21	26	20
Osaka	1950-58	26	32	33	23	32	28	30	31	30	28	26	32	29
Kobe	1947-58	29	27	26	23	24	22	23	22	24	24	25	26	24
Sumoto	1952-58	23	18	17	21	22	21	19	<i>17</i>	18	23	22	24	20
Uno	1957-58	21	22	22	23	22	16	19	<i>15</i>	19	23	24	24	20
Kure	1951-58	34	34	32	30	32	29	31	31	31	30	31	33	32
Komatsujima	1953-58	21	21	<i>18</i>	22	19	20	20	21	22	21	19	24	21
Takamatsu	1949-58	26	27	28	25	24	<i>19</i>	25	25	23	26	23	26	25
Matsuyama	1950-58	23	26	25	22	22	18	<i>17</i>	20	22	22	22	24	22
Uwajima	1949-58	18	22	21	21	20	17	<i>16</i>	<i>16</i>	22	18	17	20	19
Shimizu	1936-58	19	20	19	19	19	<i>18</i>	18	21	20	24	20	20	20
Kochi	1950-58	17	19	20	19	20	<i>16</i>	21	20	20	25	21	22	20
Aburatsu	1946-58	16	18	18	17	<i>16</i>	17	23	21	22	20	17	19	19
*Minamata	1951-53	24	<i>18</i>	32	23	23	25	32	22	33	62	—	25	(29)
Megami	1936-58	25	24	28	23	20	<i>19</i>	23	21	23	23	20	22	22
Fukabori	1957-58	18	15	25	17	19	16	17	16	19	<i>14</i>	<i>14</i>	18	17
Shimonoseki	1953-58	27	24	23	20	19	18	<i>14</i>	23	21	22	19	20	21
Tonoura	1936-58	20	21	23	25	19	17	16	<i>15</i>	18	21	21	17	19
Sakai	1951-58	19	20	22	20	18	18	<i>15</i>	15	17	21	18	19	18
Iwasaki	1951-58	18	20	21	21	22	17	<i>14</i>	16	19	19	19	20	19
Chichi-jima	1942-43	15	16	14	13	9	14	10	10	13	15	15	24	14

* The accuracy of data is not satisfactory.

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Table 3. The greatest value of positive anomaly above predicted sea-level in each month at tidal stations where the period of data is more than five years (in cm).

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Period
Kushiro	49	50	35	26	56	22	46	49	56	30	30	31	1952-58
Miyako	31	33	60	35	34	21	21	25	37	37	33	46	1942-58
Ayukawa	26	33	26	33	25	24	33	22	39	37	29	37	1949-58
Mera	32	44	33	38	29	30	38	78	112	75	51	39	1936-58
Tokyo	41	62	57	58	41	33	114	57	95	84	36	82	1950-58
Ito	32	46	33	35	29	61	32	52	52	39	45	38	1936-58
Uchiura	35	35	41	32	31	33	46	51	58	50	42	49	1936-58
Nagoya	45	44	34	42	61	47	34	67	125	124	75	59	1951-58
Toba	33	44	50	39	39	33	33	41	101	33	42	49	1950-58
Kushimoto	61	47	44	29	41	44	39	65	113	63	39	37	1936-58
Wakayama	37	36	41	37	43	41	38	60	113	89	45	42	1949-58
Tannowa	34	37	25	29	26	38	23	46	94	32	47	43	1954-58
Osaka	59	64	64	55	64	74	65	58	237	108	40	60	1950-58
Kobe	42	44	60	69	54	99	52	70	167	115	41	49	1947-58
Sumoto	35	33	37	33	50	35	26	46	66	32	34	43	1952-58
Kure	43	40	42	40	45	42	38	46	130	123	42	44	1951-58
Komatsujima	29	42	27	31	40	30	23	63	57	34	24	39	1953-58
Takamatsu	48	47	64	45	45	42	43	75	120	130	39	45	1949-58
Matsuyama	37	33	46	32	35	28	31	41	142	141	32	65	1950-58
Uwajima	36	47	35	28	34	30	29	49	99	71	70	38	1949-58
Shimizu	47	40	42	31	48	36	54	45	100	78	41	43	1936-58
Kochi	28	25	28	24	26	49	91	57	73	77	27	32	1950-58
Aburatsu	37	30	26	27	27	27	116	56	69	69	27	30	1946-58
Megami	48	77	38	41	32	33	39	81	81	47	36	61	1936-58
Shimonoseki	23	29	34	31	30	29	39	66	73	29	23	54	1953-58
Tonoura	54	31	40	38	28	45	41	39	57	29	31	57	1936-58
Sakai	33	36	33	30	24	22	26	31	45	31	28	45	1951-58
Iwasaki	79	46	31	45	38	27	29	39	133	34	40	41	1951-58

The greater part of our data was collected from "Monthly Report of Tidal Observation" (Kencho-Gaiho, reported from respective meteorological observatories) and "Geophysical Review" (Kisho-Yoran, published by the Japan Meteorological Agency), in which we find the anomaly of sea level from predicted one, but the accuracy of materials is not necessarily sufficient because they are calculated for high and low waters only. The remainder was collected from several reports^{(1), (2)} of storm tides due to typhoons, where the anomaly of sea level is calculated every hour or every three hours.

As a measure representing the characteristic strength of meteorological tides we shall use the maximum anomaly of sea level in each month in positive

Table 4. The greatest value of negative anomaly below predicted sea-level in each month at tidal stations where the period of data is more than five years (in cm).

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Period
Kushiro	29	30	30	25	22	16	30	44	44	24	32	24	1952-58
Miyako	47	53	23	27	21	22	20	21	27	23	28	45	1942-58
Ayukawa	23	23	28	17	27	38	20	21	28	41	21	22	1949-58
Mera	46	34	26	44	29	30	25	24	26	32	28	37	1936-58
Tokyo	33	34	38	33	30	23	34	25	41	49	29	37	1950-58
Ito	51	33	31	52	35	25	24	36	28	43	29	32	1936-58
Uchiura	33	31	33	49	31	35	26	26	32	41	38	52	1936-58
Nagoya	35	28	31	24	28	25	23	28	39	32	41	34	1951-58
Toba	23	22	32	34	22	28	29	23	28	28	23	28	1950-58
Kushimoto	26	24	43	52	24	26	30	33	34	35	35	38	1936-58
Wakayama	32	31	29	45	35	32	30	30	30	30	30	34	1949-58
Tannowa	25	23	23	28	27	21	21	30	25	24	24	30	1954-58
Osaka	34	42	68	33	67	38	37	39	37	36	33	39	1950-58
Kobe	55	61	37	29	30	26	28	29	41	33	34	33	1947-58
Sumoto	32	24	23	24	33	30	22	22	22	32	32	34	1952-58
Kure	40	40	40	38	37	33	39	41	39	40	37	45	1951-58
Komatsujima	27	24	21	28	24	27	24	25	32	28	26	30	1953-58
Takamatsu	36	38	44	32	31	31	40	37	28	44	30	30	1949-58
Matsuyama	31	53	31	29	30	24	19	37	27	32	24	29	1950-58
Uwajima	23	37	31	32	39	25	27	20	32	20	23	23	1949-58
Shimizu	31	31	32	32	33	27	31	74	43	55	32	33	1936-58
Kochi	20	23	34	26	40	20	37	29	26	66	29	39	1950-58
Aburatsu	22	27	26	34	20	30	76	60	36	32	22	32	1946-58
Megami	49	42	61	40	38	32	36	38	44	74	33	46	1936-58
Shimonoseki	37	31	28	26	25	24	20	43	27	25	33	25	1953-58
Tonoura	47	38	38	64	40	29	34	28	23	38	38	31	1936-58
Sakai	23	31	26	25	22	27	22	21	24	31	27	22	1951-58
Iwasaki	26	27	31	29	30	21	19	21	24	32	29	25	1951-58

and negative cases, and we calculate monthly means and annual means of them in two cases, respectively. The result is listed in Tables 1 and 2. The greatest anomaly in each month is shown in Tables 3 and 4.

3. Regional distribution of meteorological tides

In the beginning let us consider the positive anomaly of sea level. Regions with the annual mean more than +30 cm are the Tokyo Bay, the Ise Bay, the west coast of Kii Peninsula, the Osaka Bay, the Inland Sea of Seto and the Kagoshima Bay (Fig. 2). In the Ariake Sea, too, we can expect great meteorological tides, though details are unknown because of the lack of exact data.

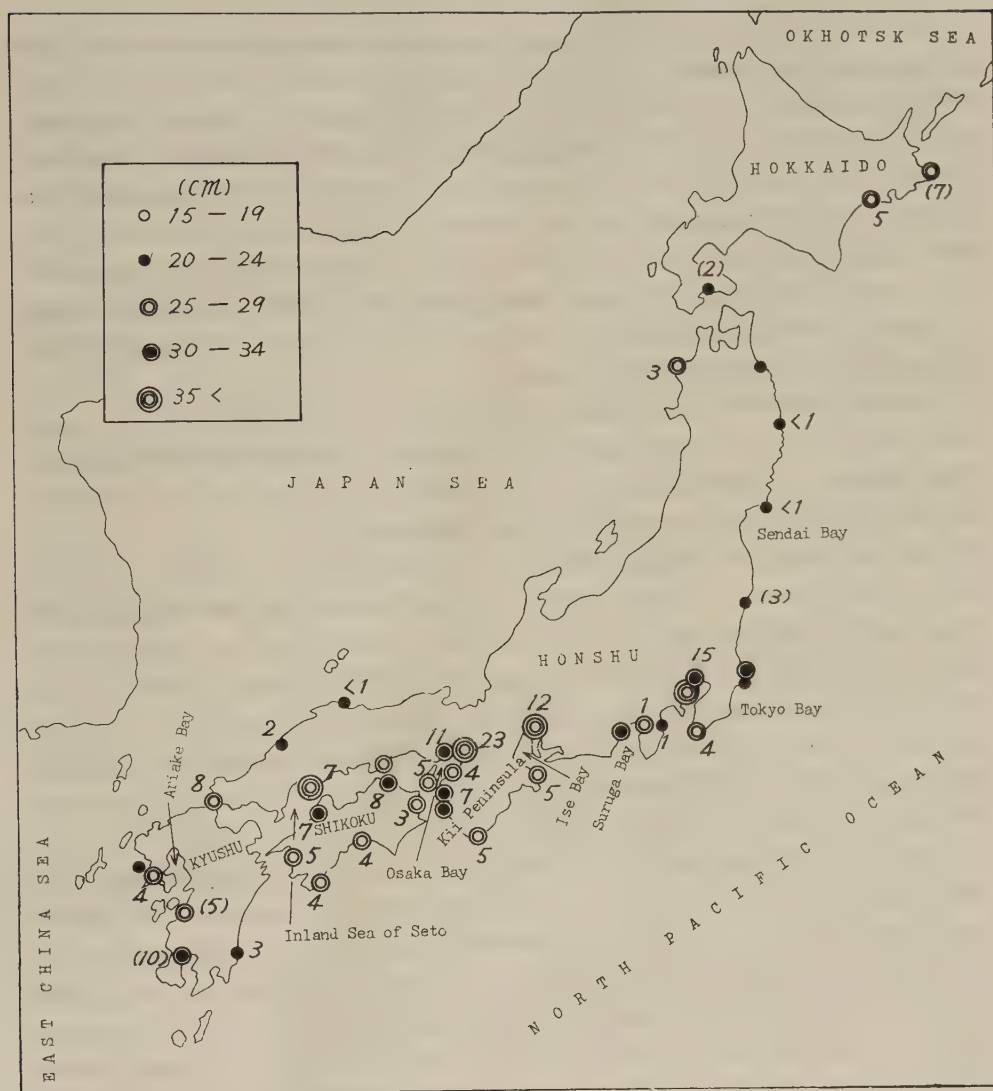


Fig. 2. Annual mean of the maximum of positive anomaly above predicted sea-level in each month (represented by the various types of circle), and frequency of positive anomaly more than +50 cm for ten years (given by the numerals close near circles).

These regions agree naturally with places where we have frequently suffered great damages by storm tides.⁽³⁾

The reason why the meteorological tides are so great at these regions may be considered as follows: (1) Topographically speaking, they are shallow waters and almost all of them are located on the southern coastline with their entrance towards the south or the southwest. (2) Meteorologically speaking, cyclones and tropical cyclones (typhoons) pass frequently in the neighbourhood of these regions accompanying with low pressure and strong southerly wind which cause upheaving of sea water at the end of Bay. For example, of many typhoons which raised storm tides for about thirty years 1927 to 1955, twenty-one landed in Kyushu, fourteen in Shikoku to Kii, eight in Kii to Kanto and none in other regions, but five typhoons did not land.⁽⁴⁾

Regions where the meteorological tides are secondarily big are the west coast of Kyushu, the south coast of Shikoku, Honshu and Hokkaido which face the Pacific directly. In those regions the topographical conditions are not so favourable, but the meteorological conditions are favourable.

The east coast of Honshu and the Japan Sea side of our country belong to places where the meteorological tides are mild because the meteorological and topographical conditions are not propitious for the development of meteorological tides, and the annual mean of positive anomaly is 20 cm or so. On the Okhotsk Sea coast of Hokkaido, too, we can expect the same circumstances. Of these regions, however, there are some places where the meteorological tides are large locally according as their peculiarity, for instance, at Iwasaki on the Japan Sea side the annual mean of anomaly reaches +28 cm.

Moreover at Chichi-jima ($27^{\circ}5'N$, $142^{\circ}11'E$) in the Bonin Islands located in the Northwest Pacific, the meteorological tides are most inconspicuous, the annual mean being +15 cm only. This is attributed to the fact that the storm is not so many and that the setup of sea water is apt to be restricted on the coast of such an isolated island. In the Suruga Bay, though its mouth faces towards the south, the meteorological tides do not develop so remarkably as in other bays mentioned above because the depth is very large. In the Sendai Bay, though the topographical features are favourable a little for the growth of meteorological tides, the anomaly is comparatively small because the meteorological conditions are not so suitable.

Here we shall touch on the number of occurrence of large anomaly (Table 5). In Fig. 2 we see that stations where the large anomaly appears frequently accord with those where the meteorological tides are large, that is, the frequency of

Table 5. Frequency when the positive or negative anomaly from predicted sea-level exceeds +50 cm or -50 cm for ten years, respectively.

Station	Case of positive anomaly													Case of negative anomaly
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Sum	
Kushiro	—	1.7	—	—	1.7	—	—	—	1.4	—	—	—	4.8	0.0
Miyako	—	—	0.6	—	—	—	—	—	—	—	—	—	0.6	0.6
Ayukawa	—	—	—	—	—	—	—	—	—	—	—	—	0.0	0.0
Mera	—	—	—	—	—	—	—	1.0	1.0	1.5	0.5	—	4.0	0.0
Tokyo	—	1.3	1.3	1.3	—	—	1.3	3.0	3.3	2.2	—	1.3	15.0	0.0
Ito	—	—	—	—	—	0.4	—	0.4	0.5	—	—	—	1.3	0.9
Uchiura	—	—	—	—	—	—	—	0.5	0.4	0.4	—	—	1.3	0.4
Nagoya	—	—	—	—	1.4	—	—	2.5	3.3	2.5	1.3	1.3	12.3	0.0
Toba	—	—	1.3	—	—	—	—	—	2.2	1.1	—	—	4.6	0.7
Kushimoto	0.6	—	—	—	—	—	—	0.6	1.7	1.7	—	—	4.6	0.6
Wakayama	—	—	—	—	—	—	—	2.5	3.8	1.0	—	—	7.3	0.0
Tannowa	—	—	—	—	—	—	—	—	4.0	—	—	—	4.0	0.0
Osaka	1.1	1.1	3.3	2.2	1.1	3.3	1.1	3.3	3.3	1.1	—	2.2	23.1	2.2
Kobe	—	—	0.9	2.7	0.9	1.7	0.8	1.7	1.7	0.8	—	—	11.2	1.7
Sumoto	—	—	—	—	2.0	—	—	—	2.5	—	—	—	4.5	0.0
Kure	—	—	—	—	—	—	—	—	4.3	2.5	—	—	6.8	0.0
Komatsujima	—	—	—	—	—	—	—	1.7	1.7	—	—	—	3.4	0.0
Takamatsu	—	—	2.0	—	—	—	—	2.0	3.0	1.0	—	—	8.0	0.0
Matsuyama	—	—	—	—	—	—	—	—	4.5	1.3	—	1.1	6.9	1.1
Uwajima	—	—	—	—	—	—	—	—	3.0	1.3	1.1	—	5.4	0.0
Shimizu	—	—	—	—	—	—	1.0	—	1.5	1.4	—	—	3.9	0.9
Kochi	—	—	—	—	—	—	1.1	1.1	1.1	1.1	—	—	4.4	1.1
Aburatsu	—	—	—	—	—	—	0.8	0.9	0.8	0.8	—	—	3.3	1.5
Megami	—	0.7	—	—	—	—	—	1.2	1.3	—	—	0.6	3.8	1.8
Shimonoseki	—	—	—	—	—	—	—	1.7	3.3	1.3	—	1.7	8.0	0.0
Tonoura	0.5	—	—	—	—	—	—	—	0.4	—	—	1.4	2.3	0.4
Sakai	—	—	—	—	—	—	—	—	—	—	—	—	0.0	0.0
Iwasaki	1.4	—	—	—	—	—	—	—	1.3	—	—	—	2.7	0.0

positive anomaly more than 50 cm for ten years is 15 times at Tokyo, 12 at Nagoya, 23 at Osaka, 11 at Kobe, 10 at Kagoshima, and the Inland Sea of Seto is second to them. On the coast of Japan Sea and the east coast of Honshu it is only one or so.

4. Distribution of negative anomaly of sea level.

Next, let us consider the negative anomaly of sea level (Tables 2, 4 and Fig. 3). The mean of it is generally smaller than that of positive anomaly. The reason for this may be attributed to the following facts:

- (1) The strength of meteorological elements such as wind velocity and

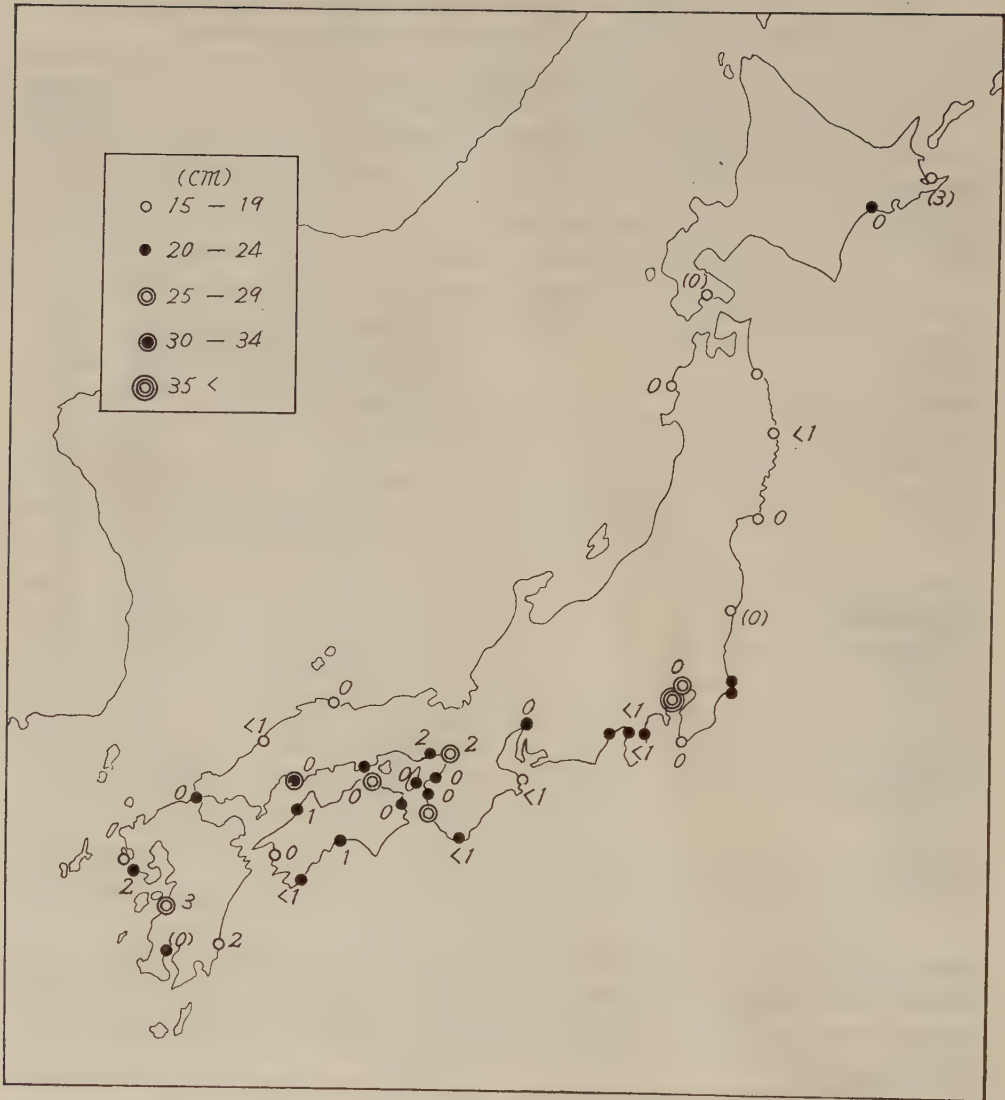


Fig. 3. Annual mean of the maximum of negative anomaly below predicted sea-level in each month (represented by the various types of circle), and frequency of negative anomaly more than -50 cm for ten years (given by the numerals close near circles).

atmospheric pressure which contribute to the variation of sea level is weaker in case of the fall of sea level than in case of the rise. Namely, the velocity of

wind blowing seawards is usually smaller than that blowing landwards, and the rising of atmospheric pressure in an anticyclone is not so conspicuous as the falling of it in a cyclone and typhoon.

(2) It is not seldom that the wind and atmospheric pressure act oppositely in changing sea level, for example, in the case when the fall of sea level is caused by a cyclone the sea level is lowered by the wind blowing seawards, but raised by the atmospheric pressure.

(3) In the case of negative anomaly its maximum value is apt to be underestimated because the anomaly was obtained for high and low waters only, while the positive anomaly was calculated every hour or every three hours in the case of remarkable storm tides.⁽¹⁾

Features of distribution of negative anomaly, however, accord with those of positive anomaly on the whole. The annual mean is greatest in comparatively large bays whose mouth is situated towards the south, with the value of about 25 cm. Regions with the second value are the south and west coasts of our country facing open seas directly. On the east coast and the Japan Sea coast the annual mean is less than 20 cm. At Chichi-jima it is smallest with the value of 14 cm.

It is very few when the anomaly with negative sign exceeds -50 cm, that is, even at Osaka the number of occurrence is only two for ten years and at Tokyo none (Table 5). In Ogura's paper⁽⁵⁾, too, the negative anomaly larger than -50 cm was not found at Tokyo for three years 1932 to 1934. But it must be kept in mind that, when the action of suction due to atmospheric pressure was excluded, the largest value of lowering of sea level due to wind only reached -80 cm.

5. *Seasonal variation of meteorological tides*

The features of seasonal variation are that two maximums appear in spring and autumn (Table 1 and Fig. 4). The maximum in spring is attributed to extratropical cyclones, and that in autumn chiefly to tropical cyclones and partly to extratropical cyclones. On the south coast of our country the maximum value in autumn is remarkably larger than in spring, for example, at Osaka it is 41 cm in the latter, but 71 cm in the former.

On the other hand, the values of two maximums are almost comparable on the Pacific side of eastern Japan and Japan Sea side, for instance, at Ayukawa

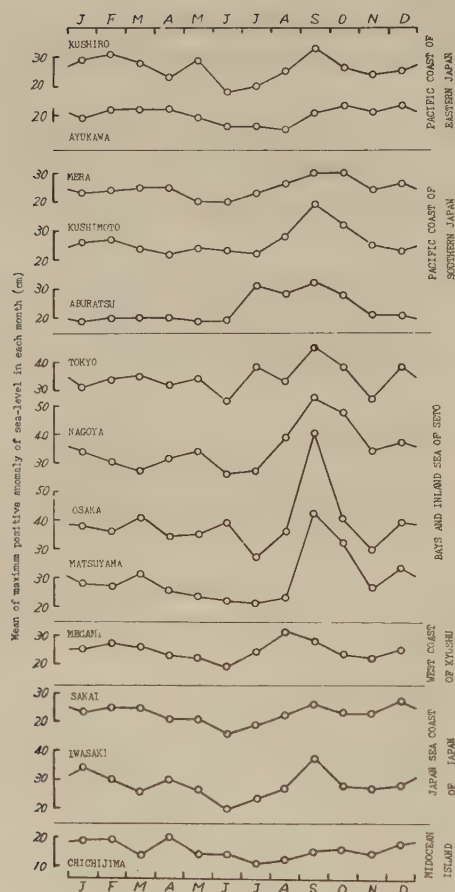


Fig. 4. Seasonal variation of positive anomaly of sea-level.

22 cm in spring and 23 cm in autumn. The season of least anomaly is June and July throughout the country, corresponding to the season when severe storms are few apart from weak ones.

With respect to negative anomaly, the features of seasonal variation is almost the same as that of the positive anomaly mentioned above, showing two maximums in spring and autumn, but the range is smaller (Table 2 and Fig 5).

Speaking of the frequency of positive anomaly over +50 cm, the following facts are recognized: (1) At the end of large bays whose entrance faces the

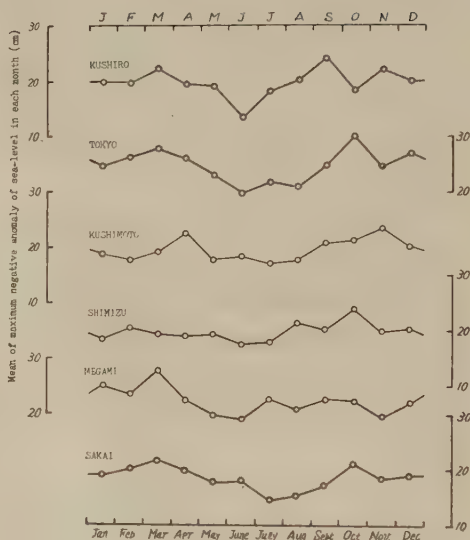


Fig. 5. Seasonal variation of negative anomaly of sea-level.

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south, storm tides are most frequent in August to October being due to typhoons, and next in March to May being due to cyclones, and this agrees with Miyazaki's result for Kobe⁽²⁾. (2) But, at stations facing the Pacific directly we have scarcely had storm tides due to cyclones in spring. (3) On the Japan Sea coast and the coast of Hokkaido, it is noticeable that the frequency of great meteorological tides due to winter monsoons and cyclones is more than that due to typhoons.

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